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Analysis of Alternatives for Out- and Over-Size Strategic Airlift: Reliability and Cost Analyses

Volume I: Main Report

W. L. Greer, Project Leader

Mar 2000

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INSTITUTE FOR DEFENSE ANALYSES

IDA Paper P-3500

Analysis of Alternatives for Out- and Over-Size Strategic Airlift: Reliability and Cost Analyses

Volume I: Main Report

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PREFACE

The strategic airlift force has the responsibility during crises and war to move combat personnel and equipment over intercontinental distances in short periods of time. The trend toward smaller U.S. forces deployed forward has placed an increasing burden on strategic airlift to move forces rapidly into deterrent and warfighting postures. Despite the new capability from the C-17s entering the fleet, there are troubling trends for the strategic airlift fleet from the older C-5s. The C-5As and Bs constitute about one-half of the current fleet but suffer from a very low reliability, significantly below that of other strategic airlifters, and—most important—below the planning level used in CINC plans and in recent mobility studies. As a result of the low C-5 reliability, the U.S. Transportation Command may have difficulty meeting wartime requirements. Basically three near-term alternatives are being considered to remedy the situation: (1) increase the reliability of C-5s through selected upgrades, (2) phase out C-5s and replace them with additional C-17s, or (3) both upgrade C-5s and acquire additional C-17s. The study contained in this document assesses the costs and reliability improvements expected for these different alternatives and their variants.

The IDA study team benefited from extensive support provided by a large number of Government offices. We wish to thank our study sponsors, the U.S. Transportation Command and the Headquarters, Air Mobility Command (AMC), both at Scott AFB, for arranging meetings, establishing contacts, and providing data in a timely and useful manner. The AMC/XP analysts also helped critique the analyses while still in the formative stages and helped identify areas needing additional attention. We especially acknowledge critical discussions with logistics personnel within AMC/LG. Elsewhere within the Air Force, we are particularly grateful for the data and information exchange meetings hosted by the C-5 and C-17 aircraft and engine system program offices (SPOs) at the Aeronautical Systems Center, Wright Patterson AFB. We also benefited from discussions with the Air Force Operational Test & Evaluation Center (AFOTEC), Office of Aerospace Systems, the San Antonio Air Logistics Center, the Warner Robbins Air Logistics Center, the Office of the Secretary of the Air Force for Acquisitions (SAF/AQ), the Air Force Cost Analyses Agency (AFCAA), the 436th Logistics Group at Dover AFB, and the C-17 Logistics Group at Charleston AFB.

Finally, we wish to thank the companies who provided the crucial technical and cost data without which this study could not have been conducted. In particular, we thank Lockheed Martin Aeronautical Systems, The Boeing Company, Rolls Royce/Allison Aircraft Engines, General Electric Aircraft Engines, and Pratt & Whitney Aircraft Engines.

The study team gratefully acknowledges expert assistance from the IDA reviewers: Dr. David L. Randall, Dr. George E. Koleszar, Dr. Phillip Gould, Dr. J. Richard Nelson, Mr. Scott L. Berg, Mr. Stanley A. Horowitz, Mr. James L. Wilson, and Ms. Deborah P. Christie.

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Part 1
INTRODUCTION AND SUMMARY

INTRODUCTION

A. BACKGROUND

Strategic airlift aircraft enable rapid deployment of U.S military forces and assistance into troubled areas around the world. Their availability and reliability are critical to deterrence and mission success. This study examines the degrading reliability of a major component of the strategic airlift fleet: the C-5s. Currently 126 C-5As and Bs are in the strategic airlift fleet (76 As and 50 Bs). The reliability of these aircraft has been steadily dropping over the last few years, an issue of growing concern within the DoD. The mission-capable rate has fallen below 65 percent, a level well below the 75 percent used as a basis for war planning.

One possible solution to the decline in C-5 reliability, hence strategic airlift fleet reliability, would be to upgrade the C-5's most troublesome systems. Some C-5 improvements are already planned. The C-5 fleet is programmed in the current USAF Program Objective Memorandum (POM) to have HT-90 turbine inserts for greater engine reliability, a full thrust reverser overhaul, and implementation of the Avionics Modernization Program (AMP) to replace older avionics with more modern and reliable ones that also ensure compliance with the new Global Air Traffic Management (GATM) requirements. We designate the POM-funded configuration the Baseline C-5, representing the C-5 as it is programmed to be in 2005 (to distinguish it from the current C-5).

More could be done than is in the POM. In 1996 Lockheed Martin Aeronautical Systems produced three studies[1] under contract to the San Antonio Air Logistics Center, the purpose of which was to identify and evaluate potential improvements in C-5 performance. These studies outlined a comprehensive modernization package that promised to bring the C-5 to levels of departure reliability and mission capable rate near

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1 *C-5A/B Modernization Study, Phases I-III*, Lockheed Martin Aeronautical Systems, 1996, PROPRIETARY.

those of other airlifters in the fleet, such as the C-17 and KC-10. With this improved reliability, Lockheed Martin also predicted lower total ownership costs over the long-term. This tantalizing possibility immediately seized the attention of decision-makers within the transportation community.

In July 1997, OSD and Headquarters AMC asked IDA to make an independent examination of the data, methods, and conclusions reached in the Lockheed studies, and to report its findings. IDA published its findings[2] in December 1997. Both the Lockheed Martin and IDA assessments identified upgrading and re-engining the C-5 as a cost-effective improvement. Both studies indicated that at least $5 billion would be needed to perform the upgrades identified, including a complete re-engining of the C-5 fleet. The more reliable upgraded C-5 aircraft would cost less to operate and provide higher confidence in meeting mission requirements. Thus, the general concept of major C-5 upgrades was validated, provided sufficient funds could be found near-term to realize long-term savings.

The Fully Upgraded C-5 of the Lockheed Martin study would add to the Baseline FY 2005 upgrades and have the additional systems depicted in Figure 1. These improvements to the C-5 have now been incorporated into the USAF C-5 Reliability Enhancement and Re-Engining Program (RERP). A Partial Upgrade was also considered in this study and includes all upgrades for the C-5 shown in Figure 1 except the power plant replacement (the most costly single replacement action).

While both the IDA and Lockheed Martin studies showed that upgrading the C-5 may be cost-effective if the C-5 is to be retained in the fleet long enough, the larger question of whether money spent for improving strategic airlift should be directed toward C-5 improvements or toward some other improvements, such as adding more C-17s, or even some of both, is an issue. That issue has became the subject of the Out and Oversize Analysis of Alternatives (AoA), led by HQ Air Mobility Command. Based on IDA's experience in the previous C-5 analysis, the U.S. Transportation Command and HQ AMC asked IDA to analyze the reliability of aircraft in alternative fleets in the AoA and to assess their life cycle costs. This document reports those analyses.

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[2] *Independent Analysis of C-5 Modernization Study*, Institute for Defense Analyses, IDA Paper P-3371, December 1997, UNCLASSIFIED/PROPRIETARY

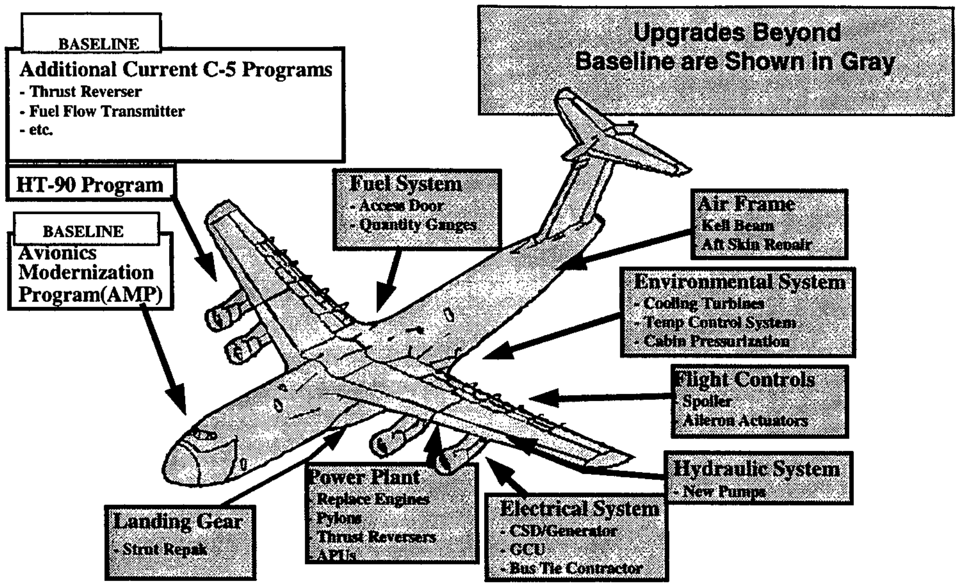

Figure 1. Concept for Fully Upgraded C-5, Including Programmed Baseline Upgrades

B. OBJECTIVE & SCOPE

The objective of this report is to assess the reliability and life cycle costs for all reasonable alternatives through the year 2040 for use in an analysis of alternatives for improving strategic airlift capabilities. This document does not directly assess fleet operational effectiveness other than through the aggregate capacity measure of million ton-miles per day (MTM/D). The Air Mobility Command has assessed the operational effectiveness and cost-effectiveness for the AoA in separate documentation.

The alternatives include a range of reasonable fleets, each with aircraft easily achievable within the next several decades, using off-the-shelf technology, and able to deliver outsize and oversize cargo. Emphasis is on delivery of outsize and oversize cargo since all strategic lift aircraft can carry bulk, but only C-5s and C-17s can carry outsize and all the oversize cargo needed.

The analysis examines the time period extending to the year 2040. It begins in FY 2000 and excludes costs already programmed for the C-5. The study also excludes costs—acquisition or operating—for the programmed 135 C-17s [120 C-17s previously programmed plus 15 recently approved special operations force (SOF) C-17s]. Thus costs that are included in this AoA are for changes to the C-5 and C-17 programs as currently funded.

C. OUTLINE OF REPORT

Volume I contains three parts: Introduction and Summary (Part 1), Discussion (Part 2) and Analyses (Part 3). As the title suggests, the Summary, which follows immediately after this section, summarizes the approach taken and the main findings of our work. In Part 2, Discussion, we provide a more detailed explanation of the findings in the Summary. Part 3, Analyses, contains the details of specific focused analyses.

The current volume, Volume I, is unclassified and meant for general use. The proprietary Volume II, available to authorized recipients only, provides additional details—some of which are company sensitive—on the projected acquisition and operating costs of the C-5 and C-17 as well as on costs and assumptions associated with different propulsion system candidates for re-engining the C-5. Volume II is important in substantiating through detailed analyses the findings cited here as well as in providing a resource for the Government to use when negotiating future programs that may follow from decisions made using the AoA.

SUMMARY

The main findings of this report are summarized in this section. The purpose of the Summary section is to provide an overview along with the main associated supporting arguments. Each topic is treated in greater detail later in the document.

We start with an assessment of the C-5 and C-17 structural replacements during the 40 years under consideration in this AoA and address the issue of structural lifetime. We then summarize our estimates of the mission-capable rates for the different C-5 and C-17 configurations. The alternative airlift fleets examined in the AoA are introduced next, followed by an assessment of their life cycle costs. The Summary concludes with a cost sensitivity and cost risk assessment for all the alternatives.

A. STRUCTURAL LIFETIMES

The aircraft alternatives considered in this AoA involve airframes that must last until at least 2040. To be viable candidates for this AoA, the aircraft considered should have a structural life that would satisfy this criterion. C-5s first entered service in 1970, and even the youngest date from the late 1980s. By contrast, the C-17s are relatively new, and many that we consider in this report will not be delivered into service until 2005 or later. Nonetheless, the C-17s are scheduled to fly a considerably higher number of hours per year than the C-5s. The net effect is that by 2040 both the C-5s and C-17s will have accumulated a large number of flying hours and experienced a significant number of fuselage pressure cycles. For this reason we need to address structural life. Will these aircraft last until 2040?

The structural issues we explore are twofold. Based on historical data and trends, we estimate (1) what structural elements in each aircraft will need replacing over this time period and (2) what the costs for these replacements would be. Most significant to all these questions is whether any widespread structural fatigue is expected during the next 40 years that would force the retirement of any of the aircraft and jeopardize the viability of any of the AoA alternatives.

We used the test-demonstrated airframe life as the basis for extrapolating C-5 structural limits. Instead of using the demonstrated life, we use one-half the actual test value reached. This is a very conservative basis, since tests do not always continue until a failure is observed. The one-half factor corrects for differences in materials, manufacturing processes, and ideal test conditions vice real operational experience. Although some aircraft outlast the tested lifetimes, this rule of thumb has proved a fairly reliable lifetime indicator in the past and we use it here.

Using wing life and fuselage pressure cycles as metrics, we find that the C-5 fleet, flying at the hours and under conditions currently experienced, will not exceed one-half the test-demonstrated values by 2040.

This is not to say that there will be no structural problems at all. In fact, we are certain that there will continue to be structural replacements needed over the next 40 years. Recent problems with the C-5A upper crown skin and horizontal stabilizer suggest that additional structural retrofits will be needed in the future if the aircraft are retained in the fleet. In our analyses we have included costs for C-5A aft fuselage upper crown skin replacement, C-5A and B landing gear and mainframe replacements, horizontal stabilizer replacements, and corrosion reworks of known problems. However, we feel that none of these structural problems would terminate the life of the C-5 before 2040, as long as retrofits and reworks are performed in a timely and prudent manner. In total, the operating cost for 126 Baseline C-5s through 2040 is estimated to amount to $588 million in FY 2000 dollars. If the same 126 C-5s were fully upgraded (including new propulsion system) as shown in Figure 1, the cost would be lower, approximately $411 million. In either case, $190 million is required near term to replace the C-5A upper crown skin.

The current C-17 possesses a considerably younger airframe than the C-5 but flies at a much more demanding pace. AMC informs us that this trend will continue. By 2040 these rates will bring C-17 fatigue use to levels comparable to those projected for the C-5 fleet. As thresholds for C-17 structural life, we used one-half the test-demonstrated value (as we did for the C-5s). Extrapolating C-17 usage in accord with current use, we find that the fuselage should encounter no fatigue limits by 2040, but that the wings will just be reaching the fatigue limits between 2035 and 2040 for the older (e.g., currently operational) C-17s. This is our low risk assessment. With somewhat higher risk, the wings will perform well without replacement beyond 2040. A number of non-life-limiting structural areas are likely to require attention. These areas in the C-17 are jack points, vertical tail-to-fuselage interface, landing gear, wing pylons, and horizontal stabilizer. In each case we have added costs into the operating and support cost estimates shown later in the summary. For example, 60 C-17s would incur about $114 million in retrofit costs through 2040, assuming wing replacements are not needed.

B. MISSION CAPABLE RATES

We have estimated Mission Capable Rate (MCR) values for all the aircraft under consideration for improving the capability of the airlift fleet. The MCR for C-17s is assumed to remain unchanged through 2040 from current values through periodic and timely maintenance actions, such as through the structural replacements and corrosion reworks just noted. The costs associated with these maintenance actions are part of the overall operating and support costs.

The MCR estimates for various upgraded configurations of the C-5 pose complex analytical questions, since these configurations represent hypothetical rather than actual aircraft. Maintenance data are available only on existing C-5 aircraft. The methodology we use to estimate the MCR for the baseline and fully upgraded C-5s is an extension of that introduced by IDA in the cited 1997 study and is further detailed in Part 3 of this volume. Briefly stated, the methodology examines the failure rate of individual components in the current C-5 aircraft and estimates the overall improvement expected from replacing them with more reliable components in an upgrade program. One major feature of the approach is its way of treating simultaneous failures of more than one component, a common occurrence in the C-5 and in any other complex and fairly unreliable system. The methodology explicitly treats masking, in which more than one component may fail, but for which the down time is attributed in the reporting system to the pacing item that requires the longest time to fix. Once the pacing item is replaced with one of higher reliability in an upgrade program, all problems do not vanish, since other failures that were not reported before are now unmasked. One of them then becomes the new pacing item.

The model is calibrated against known reliability measures for the current C-5 fleet. We then use the same calibration factor in estimating reliability measures for the baseline and upgrade configurations already discussed. A validation of the analyses was conducted and is included in the more complete description in Part 3.

Table 1 summarizes the average MCR for the current C-5 configuration and for all the aircraft configurations considered in the AoA for three different operating tempos: Peacetime, Surge, and Sustained. Peacetime refers to normal day-to-day operations, including planned maintenance actions. During Surge conditions, the planned maintenance and Home Station Checks are waived. During Sustained tempos, some of the planned maintenance is waived, but Home Station Checks are reinstituted. The new maintenance concept involving commercial letter check procedures (in lieu of Programmed Depot Maintenance (PDM) and other regularly scheduled maintenance actions) is currently under consideration within the USAF and is automatically included in all upgrade configurations beyond the Baseline. Commercial inspection procedures (for which the "C" check is closest to what is intended here) are performed annually and take less overall time than the military maintenance programs it would replace.

To indicate the importance of letter check in improving reliability, the MCR with and without letter check is shown for the current (1999) and Baseline (2005) C-5 configurations. The main contribution to the MCR is from a new definition of what constitutes a possessed aircraft, although there are some tangible reliability enhancements, too. Letter check has no impact on Surge MCR, since during the Surge environment the PDM and other planned maintenance are deferred. Letter check has a large impact on peacetime and sustained environments. We assume full supply support in the upgraded C-5s. The AoA typically cites the sustained MCR values when selecting a single set of numbers for comparison in the context of Major Theater Wars (MTWs).

Table 1. Summary of Strategic Airlifter Mission Capable Rates
Percent Mission Capable Aircraft

Aircraft Configuration	Peacetime	Surge	Sustained
Current C-5			
Without Letter Check	61.9	70.3	63.9
With Letter Check	67.0	70.4	67.7
Baseline C-5			
Without Letter Check	62.1	70.4	64.0
With Letter Check	67.2	70.4	67.8
Partial Upgrade C-5 with Letter Check	70.0	74.9	72.3
Full Upgrade C-5 with Letter Check	73.5	78.2	75.6
C-17	85	90	87.5

C. AoA STRATEGIC AIRLIFT FLEETS

To assist in deciding whether upgrading C-5s or buying additional C-17s is the most cost-effective solution, AMC has proposed alternative fleets and analyzed them for cost (this study) and effectiveness (AMC study). AMC selected these alternatives to span their decision space.

The MCR values from Table 1 were used to construct the alternatives. Headquarters AMC used the MCR values for individual strategic aircraft types and generated alternative fleets, many with comparable capacities as measured by millions of ton-miles per day (MTM/D, an aggregate measure often used in airlift analyses). One of the terms used in estimating MTM/D is the utilization (ute) rate, a figure strongly dependant on MCR. The alternatives are summarized in Table 2, along with their associated MTM/D capacities. The MTM/D values are for the full set of C-5s and C-17s in each alternative, including the 120 C-17s already programmed.

Table 2. AoA Alternatives Used for Life Cycle Costing

Alternative	MTM/D	C-5 Configuration		Additional C-17 Aircraft Beyond 135
		C-5A	C-5B	
1	24.9	Baseline	Baseline	0
2	27.1	Baseline	Baseline	20
3	30.1	Baseline	Baseline	45
4	27.8	Baseline	Full Upgrade	20
5	30.7	Baseline	Full Upgrade	45
6	27.2	Full Upgrade	Full Upgrade	0
7	32.3	Full Upgrade	Full Upgrade	45
8	27.7	0	Full Upgrade	75
9	27.9	0	0	132

The required value for the capacity in MTM/D will come from the yet-unfinished 1999 Mobility Requirements Study 2005 (MRS-05). AMC estimates that it will exceed values validated by the previous strategic lift study, the 1995 Mobility Requirements Study Bottom-Up Review Update (MRS BURU). In that study, the required capacity for oversize and outsize (O&O) cargo alone was 27.1 MTM/D.

There are nine AoA alternatives, not including all the excursions based on these nine. Alternative 1 is the programmed strategic airlift fleet: Baseline C-5s and C-17s. Its composition represents the POM fleet in 2005, if no alterations to the POM are made. Note that Alternative 1 has an O&O capacity of 24.9 MTM/D, well short of the 27.1 MRS BURU requirement cited above.

The remaining eight alternatives add capability to reach or exceed the MRS BURU requirement in different ways. Alternatives 2 and 3 retain the Baseline C-5s but add additional C-17s beyond those programmed (Alt 2 adds 20 C-17s while Alt 3 adds 45). Alternatives 4 and 5 retain Baseline C-5As but fully upgrade the C-5Bs and add additional C-17s (Alt 4 adds 20 C-17s while Alt 5 adds 45). Alternative 6 fully upgrades all 126 C-5s but otherwise adheres to the C-17 program by adding no additional C-17s. Alternative 7 adds 45 C-17s to Alternative 6. All alternatives through 6 retain 126 C-5s, although their configurations differ. Alternatives 8 and 9 reduce the number of C-5s while adding C-17s. To be specific, Alternative 8 retires the C-5As and adds 75 C-17s while Alternative 9 retires all C-5s and adds 132 C-17s.

The 45 C-17s in Alternatives 3, 5, and 7 correspond to the recent Boeing proposal to sell the USAF 60 additional C-17s beyond the 120 currently on contract. Only 45 of the 60 are counted for costing (and effectiveness) purposes, the other 15 being used for SOF missions and therefore fenced from consideration here. Thus, Alternatives 3, 5, and 7 have higher MTM/D values than all the rest of the alternatives because they include the Boeing package whose inclusion raises the MTM/D over the MRS BURU requirement. Additional alternatives that are not currently included in the AoA are treated as excursions in this paper and are explained more fully in the Analysis section of this volume and in Volume II.

D. SUMMARY OF COST RESULTS

The main focus in this document is cost and primarily life cycle cost (LCC). The level of detail in the analyses is that required by the USAF and OSD for a defensible AoA. For the purpose of costing alternatives, we assumed that all programmed modernization costs not related to the C-5 RERP are sunk and are excluded from our comparisons. They are common costs to all alternatives and therefore not cost discriminators. We thus consider the cost of completing the buy of 120 C-17s and of the additional 15 SOF C-17s to be sunk, along with their operating costs. The only C-17 costs included in this AoA are those for additional C-17s beyond the 135 already programmed. More detail on the approach can be found in the Analysis section (Part 3 of this volume) and in Volume II.

We assessed the costs of acquisition, operations and support (O&S), and disposal through the year 2040. Table 3 summarizes the total life cycle cost over that period of time for all nine alternatives. The results are given in constant FY 2000 dollars, discounted FY 2000 dollars, and then-year dollars. Constant FY 2000 dollars allow comparisons over different time periods without the complicating inflation factor. Discounted dollars are also expressed in FY 2000 dollars, but are adjusted to account for the year in which funds are expended. Delays in expenditures, other things being equal, result in a lower discounted cost. Discounting favors future expenditures over near-term ones, something not captured by using constant dollars alone. Discounting is the approach mandated by the Office of Management and Budget (OMB) for acquisition decisions, and we have used their most recent published discount factor (2.9 percent per year) in our analyses. Then-year dollars represent the estimated actual outlay of funds through 2040, including inflation.

In all three cases, the least costly option is Alternative 6, a full upgrade to the C-5 fleet with no additional C-17s. Since Alternative 6 differs from Alternative 1 only in whether the C-5s are fully upgraded (Alt 6) or not (Alt 1), Table 3 makes clear that the $5 billion required for the upgrades in Alt 6 more than pays for itself in reduced operating costs over the 40-year period examined.

Table 3. Summary of LCC Results by Alternative
(All results in $B)

Alternative	C-5 Configuration		Additional C-17 Aircraft Beyond 135	LCC in Constant Dollars ($FY 2000)	LCC in Discounted Dollars ($FY 2000)	LCC in Then-Year Dollars
	C-5A	C-5B				
1	Baseline	Baseline	0	60.56	32.92	98.57
2	Baseline	Baseline	20	72.47	40.83	115.55
3	Baseline	Baseline	45	87.31	50.40	137.00
4	Baseline	Full Upgrade	20	70.27	40.43	110.68
5	Baseline	Full Upgrade	45	85.11	50.00	132.13
6	Full Upgrade	Full Upgrade	0	56.78	32.56	89.50
7	Full Upgrade	Full Upgrade	45	83.53	50.04	127.93
8	0	Full Upgrade	75	80.25	49.02	120.96
9	0	0	132	88.38	55.40	129.39

The analysis so far has emphasized LCC. Near-term costs may also be important for decisions, since the alternative with the lowest LCC may still not be affordable in the near term. Table 4 below summarizes (in then-year dollars) the total cost during selected time periods. The first time period is for FY 2000 and FY 2001. Note that Alt 1 shows no costs over this period, since it is in accord with programmed funds and incurs no additional costs. Alts 2, 3, and 9 also do not involve upgrades to the C-5s and also incur no costs during this same period of time. Other alternatives begin upgrades to the C-5 over this same period and incur some small additional costs.

The second period is from FY 2002 through FY 2007. This is the time period of the next POM. Here Alt 1 is less costly than any other alternative, since Alt 1 does not include upgrading the C-5, nor does it include additional C-17 purchases. Alt 6 is lower in cost than any of the other upgrade/buy alternatives over this same period.

In the third time period, the costs associated with FY 2008 through the end of the life cycle, FY 2040, are shown. Alt 6 is the least costly over this time period, as the upgrades begin to manifest themselves in reduced O&S costs. The totals from FY 2000 through FY 2040 are in the last column.

Table 4. Summary of Costs by Time Period (Then Year $B)

Alt	FY 00-FY 01	FY 02-FY 07	FY 08-FY 40	TOTAL LCC
1	—	6.86	91.74	98.57
2	—	12.36	103.20	115.55
3	—	19.07	117.93	137.00
4	0.36	14.14	96.18	110.68
5	0.36	20.85	110.92	132.13
6	0.52	9.59	79.39	89.50
7	0.52	21.83	105.58	127.92
8	0.36	22.44	98.15	120.96
9	—	20.45	108.94	129.39

E. COST SENSITIVITY & RISK ANALYSES

In this section we explore how sensitive the presented analyses are to different key cost assumptions. First, we examine how individual assumptions about key costs influence results. We select costs about which there could be the largest disagreement or which are the most influential. Then we show results of a more complete risk assessment in which the uncertainties in several cost elements are considered simultaneously.

We summarize the particular sensitivity analysis assumptions that are varied in Table 5. In general the excursions represent uncertainties in our assumptions. Different analysts might estimate differently. The key variables we examine are (1) the cost of the C-17 program for additional C-17s, (2) the type engine (thrust level) to be used in a C-5 re-engining, (3) the number of hours per year that the C-5 and C-17s will fly in each alternative, (4) the cost of fully upgrading the C-5s, and (5) the cost if re-engining is not included in the C-5 upgrades. Results for three of these are discussed next, with the rest relegated to Part 2.

Table 5. Excursions

Variable Whose Sensitivity is Examined	Basic Assumptions	Excursion
C-17 Acquisition Cost	Extrapolations from past acquisition cost plus USAF cost projections for remaining C-17s to be built	Boeing proposal, which is lower than IDA projections
Thrust Needed by New C-5 Engine	Commercial 60,000 lb thrust engine derated to 50,000 lb thrust	Commercial 43,000 lb thrust engine, comparable to current TF39 thrust, but more reliable
C-5 & C-17 Flying Hours	Current values	Revised AMC values
C-5 Modernization Program Cost	Estimates based on IDA review of C-5 RERP estimates, with changes	Revised higher cost estimates from C-5 RERP
Extent of C-5 Upgrade	AMC considered no partial upgrades to the C-5 as AoA candidates	A partial C-5 upgrade without engine replacement

1. Lower Cost C-17

Our cost estimates for additional C-17s involve an extrapolation from current costs. In March 1999, the Boeing Company submitted a proposal to the Air Force to supply an additional 60 aircraft at an average recurring flyaway price lower than that obtained from extrapolation of past cost experience and USAF budget projections for completing the 120 aircraft buy. As an excursion, we have examined how the fleet LCC would change if the Boeing proposal were used as the basis for estimating C-17 acquisition costs for aircraft beyond 120.

The costs of alternatives with additional C-17s are reduced, but the overall conclusions reached earlier do not change except for the most costly alternatives. Alternative 6 still is the least costly. This is shown in Figure 2, where the two results—the IDA cost estimates (basic) and the Boeing prices (lower C-17 cost)—are shown side-by-side.

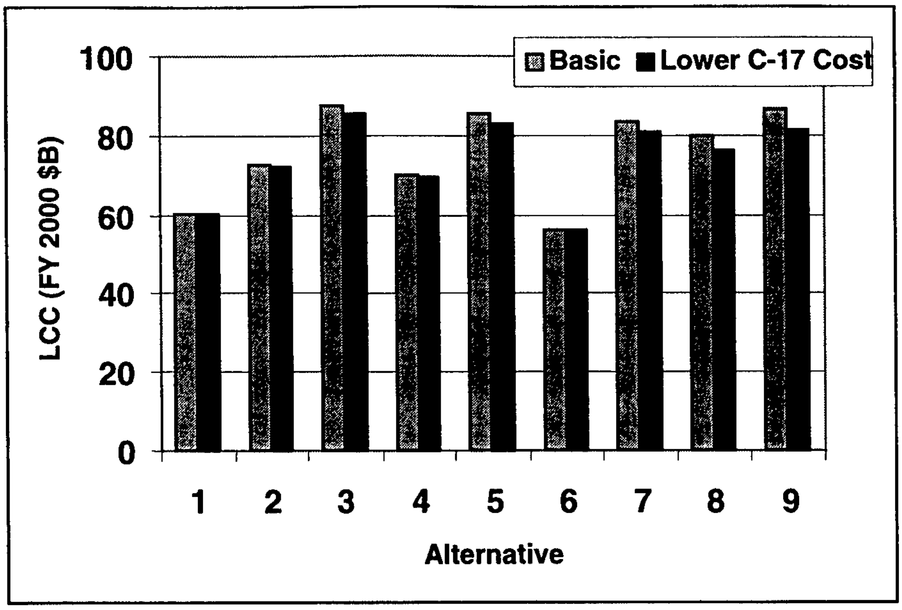

Figure 2. Comparison of LCC Results for Basic and Low Cost C-17 Assumptions

It is our understanding that the USAF uses the Boeing prices for the C-17 as the base case for the AoA. Since the relative cost rankings of the six lowest cost alternatives are not altered in this excursion, decisions made would be the same using either the basic or the lower C-17 cost excursion.

2. Low Thrust C-5 Engine

The current plan for re-engining the C-5 is to use an engine in the 60,000-pound thrust class, de-rated to 50,000 pounds. This is the assumption made in the basic analyses. As alternatives, several engines are currently available commercially in the 40-50,000 pound class, for example, the latest version of the Pratt & Whitney F-117, currently used on the C-17, or the Rolls Royce RB211-535. New engines in this same class are currently undergoing testing, so there is a potential competition within this class of engines if a lower thrust (comparable to that currently on the C-5) were acceptable. Because the lower thrust engine brings all the reliability enhancements so often cited as the reason a new engine is needed, but at lower cost and lower weight, it is a reasonable alternative to consider.

We show results for Alternative 4, upgrade the C-5B fleet only and retain the current C-5A fleet, and Alternative 6, upgrade both the C-5A and C-5B fleets. These are compared in Table 6. These two exhaustively cover all cases of comparative interest.

Alternatives 1, 2, and 3 do not involve any C-5 upgrades; Alternative 5 is the same as Alternative 4 with respect to the C-5 fleet. Alternative 8 can be "covered" by the Alternative 4 analysis, since it too also involves upgrading only the C-5B fleet, but differs from Alternatives 4 and 5 in that the C-5A fleet is eliminated. Alternative 7 is the same as Alternative 6 with respect to the C-5 fleet and Alternative 9 eliminates the complete C-5 fleet.

Table 6 shows the final results for Alternatives 4 and 6 showing both the engine LCC and the total fleet LCC. The engine LCC values include, pylons, installation, management and fees in addition to the engine procurement and O&S costs. Note that for Alternative 4, the engine LCC values represent only the C-5B fleet (the engine O&S costs for the C-5A fleet are about $7.6 billion). However, the total LCC values include all aircraft,

Table 6. LCC Results Comparing the 40,000k Engine to the 50,000k Engine Alternatives 6 and 4

Alternative		LCC Costs (FY 2000 $B)	
		C-5 Engine LCC	Total Alt LCC
Alt 4			
Re-Engine C-5B	60k	6.67	70.27
	40k	6.19	69.79
Alt 6			
Re-Engine C-5 A & B	60k	12.38	56.78
	40k	11.38	55.78

We seen from the table that for Alternative 6, the 40,000-pound thrust engine yields a 8.1 percent savings, or $1 billion, if just engine LCC is considered. From a total LCC perspective, however, this saving amounts to less than 2 percent of the total life cycle cost.

The results for Alternative 4 are in the same direction, but since a smaller portion of the total airlift fleet is being re-engined, the total LCC percentage savings are on the order of 0.7 percent.

The C-5 RERP endorses the higher thrust engine. Its Draft Operational Requirements Document (ORD) explicitly calls for a new engine with capabilities (take-off distance, climb rate) only attainable with the higher thrust engine. The RERP argues that the higher performance is worth the few percent difference in cost.

3. Partial Upgrade

A reasonable question to ask, when facing the large costs associated with upgrading C-5s or acquiring new C-17s, is what would be the cost (and capability) for a partial upgrade in which all C-5 upgrades *except for re-engining* are implemented. This excursion examines that question.

The AoA conducted by AMC considers only one C-5 upgrade option: Full Upgrade, including new engines of a de-rated 60,000-pound thrust class. We discussed the cost consequences of a lower thrust engine in an earlier excursion. Here we examine the cost and capability consequences of no new C-5 engine at all, but with the other reliability enhancements still included. As noted elsewhere in this paper, we refer to this C-5 configuration as the Partial C-5 Upgrade. Since the new engine acquisition cost accounts for nearly 75 percent of the full upgrade cost, a partial upgrade suggests itself as a reasonable alternative to investigate. Is it lower in cost overall than fully upgrading C-5s? The answer turns out to be no. The Full Upgrade costs more in acquisition but is lower in life cycle cost. We show the details below.

We have conducted a cost analysis of two excursions with partial C-5 upgrades. One is the same as Alt 6 except that no re-engining costs are included. Other engine-related costs associated with a new engine were also identified and deleted for this excursion. By estimates made by AMC, the partial upgrade excursion falls short in capacity (measured in MTM/D) from that required in MRS BURU and presumably required in MRS-05. To attain the 27.1 MTM/D capacity for over- and outsize cargo that MRS BURU required, 10 additional C-17s must be acquired to make up the shortfall for a partial upgrade option. Thus the second partial upgrade excursion we consider is identical to the first as far as C-5 upgrades are concerned but possesses 10 additional C-17s.

A partial upgrade (with no additional C-17s) reduces the fleet LCC by nearly $0.5 billion. This indicates the value of all the upgrades other than the engine replacement. Such upgrades also increase the MTM/D capacity from the Baseline, although they fall short of the goal. On the other hand, the addition of enough C-17s to attain the goal capacity of 27.1 MTM/D incurs a large cost increase. The LCC for the partial upgrade excursion then rises to $36.5 billion, well above the $32.6 billion LCC for Alt 6.

Our analyses show that, even though the C-5 re-engining is costly, the LCC for a re-engined C-5 fleet is lower than one without re-engining. The less costly re-engined C-5 fleet also has a higher MTM/D capacity than one not re-engined. When comparable capacity is required, the alternative with re-engined C-5s (Alt 6) is considerably less costly than the partial upgrade excursion with no re-engined C-5s, since additional C-17s must be bought and operated. As noted earlier, the O&S costs for these additional 10 aircraft account for all of the cost increase over Alt 6.

4. Cost Risk Analysis

The previous sensitivity analyses address the effects of varying a single important factor such as C-17 acquisition cost or introducing a partial C-5 upgrade on life cycle cost. To assess the overall cost risk for each alternative we must vary multiple factors simultaneously, not just one at a time. This section summarizes our work in this area.

The risk analysis approach does not use a single value for the cost of the important factors, but instead associates a specified uncertainty with each factor through a probability distribution of cost estimates for each factor. This leads in turn to a distribution of life cycle costs for each alternative rather than to the point estimates cited earlier. We generated cost probability distributions for each important factor over a reasonable range of costs. A statistical sampling model with 5,000 iterations was used to calculate the life cycle cost distributions.

The cost risk factors we selected are those that drove overall life cycle costs or ones that were contentious. The factors used were

1. C-5 Cost Factors
    - RERP
        - Engineering and Manufacturing Development
        - Procurement
            - Airframe
            - Engine
    - O&S
        - Failure-related risk costs: GSD/FH and MSD/FH
        - Engine

- Other non-engine O&S costs: maintenance manpower, sustaining engineering, depot maintenance (aircraft level including letter check and excluding engine), R&M and safety modifications,

2. C-17 Cost Factors
   - Aircraft procurement
   - O&S
     - Engine
     - Other non-engine

For each of the above factors, we assigned a probability distribution representing the uncertainty or risk in our estimate of the cost. In most cases we had a reasonable basis for a low and high estimate but not the form of the distribution. We used a triangular distribution, with the peak at our best estimate. Details are in Part 2 of this volume and in Volume II.

Results are illustrated in Figure 3 for the life cycle cost distribution in constant year dollars for each alternative. The distributions are peaked at approximately the point estimates used elsewhere in this document. This indicates that the point estimates are at approximately the 50th percentile. That is, with 50 percent confidence, the life cycle cost will not exceed the point estimates for the alternatives.

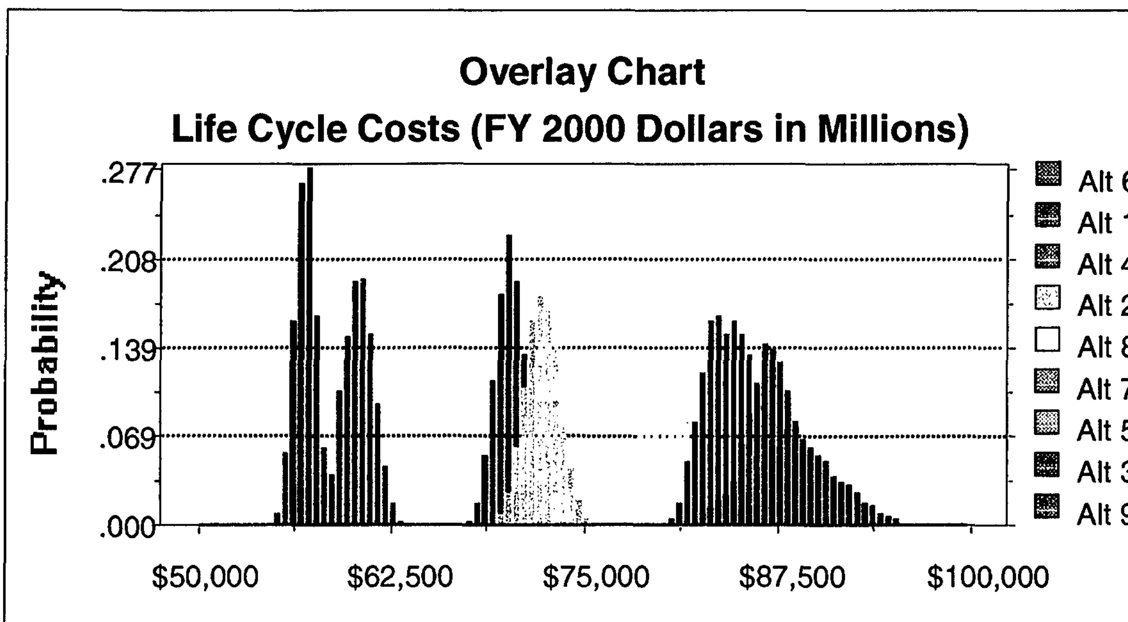

Figure 3. Life Cycle Cost Distributions – Constant Year Dollars

The distributions can also be used to define costs at higher confidence levels. As an illustration, the cost of Alt 6 (with a point estimate for the LCC of $56.8 billion in constant dollars) will not exceed $58 billion with 90-percent confidence, based on the cost elements we chose to vary.

When the Boeing C-17 costs are used, similar graphs are obtained. Details of these excursions can be found in Part 2 of this volume and in Volume II.

F. CONCLUSIONS

This study has focused on upgrades to the C-5 that can raise the mission-capable rate and on the cost of acquiring and maintaining alternative airlift fleets with different compositions of C-5s and C-17s. These costs are to be used with the effectiveness analyses conducted separately by AMC.

We have assessed the MCR of the different C-5 and C-17 configurations proposed to rectify the drop in strategic airlift capability. We estimate that the full upgrade proposed for the C-5 would raise the wartime sustained MCR above 75 percent, the goal of any modernization program. The results are summarized in Table 1 at the beginning of this section (page 8).

We have also assessed the life cycle cost of the nine alternatives proposed by AMC for the AoA, as well as a number of excursions to these alternatives. The costs are summarized in Table 3. The lowest cost alternative, Alt 6, involves a full upgrade including re-engining and no additional C-17 acquisition beyond those already planned. This alternative remains the lowest in cost for virtually all excursions.

We have subjected the cost analyses to an extensive cost risk assessment. We have varied the cost assessments of the items that are subject to the greatest uncertainty or that carry the greatest weight in determining the life cycle cost. We find that the point estimates are excellent determinants of the relative costs for the lower cost alternatives. The higher cost alternatives (Alts 3, 5, 7, 8, and 9) tend to have considerable overlap in cost distributions, although the peaks in the cost distributions retain the same relative sequences as the point estimates. We also note that, in all cases, the point estimates we presented in tables represent approximately the 50-percent confidence level for the costs.

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Part 2

DISCUSSION

DISCUSSION

A. INTRODUCTION

Strategic airlift has taken on an increasingly pivotal role in the last decade as the United States has withdrawn permanently stationed forces from abroad, only to be forced to reintroduce them in rapidly mounting crises. The need for swift and assured movement is critical, both as a deterrent, and as a means of introducing first combat units ready to fight. Ships are expected to deliver the vast majority of equipment and supplies, but the lengthy travel time from the United States or at-sea preposition locations to likely hot spots abroad places a heavy burden on airlift to bring the first forces and equipment to the theater. The aircraft that the USAF Air Mobility Command owns and that would be tasked in this strategic mission by the U.S. Transportation Command are the C-141s, C-5s, and C-17s.

The nature of the strategic lift forces is changing. Instead of three different strategic military airlifters, there will only be two by 2005. As C-141s retire from service, new C-17s will supplant them. The C-5s are currently being retained in the POM, although they continue to exhibit declining reliability. Overall, the capability of the strategic airlifter fleet will decrease unless remedial actions are taken.

In this section we introduce the basic airlift problem and identify the objective of the study.

1. Background

Because of their drop in reliability, the focus of most of the analyses in this document is on C-5s. One way to restore fleet reliability is through major upgrades.

Currently 126 C-5As and Bs are in the strategic airlift fleet. Today's allocation of the C-5 squadrons is shown in Table 7. As the table shows, most of the As are in the Guard and Reserve fleets; all the Bs are in active-duty squadrons. The distinction between Guard/Reserve and active is important for costing purposes because aircraft are maintained and flown differently in these categories.

Table 7. Number and Status of Current C-5A and C-5B Aircraft

Status	C-5A	C-5B
Active	20	44
Guard	12	0
Reserve	28	0
Training	6	0
Backup	10	6
Total	76	50

The C-5 fleet suffers from poor reliability, as is apparent from an examination of Mission Capable Rates (MCRs) and departure reliabilities (DRs). The chart in Figure 6 summarizes these two common measures of reliability for strategic airlift aircraft and compares the C-5 with the older C-141s and the more modern C-17s and KC-10s. In both charts, the C-5A and B status is shown in the dark bars. The C-5 fleet is in a noticeably reduced state of preparedness relative to other aircraft in the strategic mobility forces.

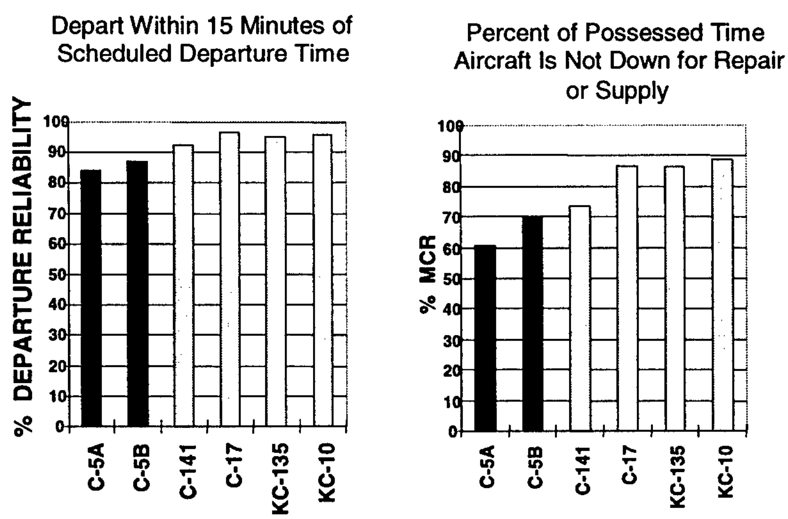

Figure 4. Summary of Current Departure Reliabilities and Mission Capable Rates for Strategic Airlifters

The departure reliability, defined as the percent of aircraft able to take off within 15 minutes of their scheduled departure times, is lower than that of the remainder of the airlift fleet. The departure reliability shown in Figure 4 is the departure reliability due to logistics and excludes weather delays and other non-maintenance delays.

The mission capable rate, the percentage of possessed aircraft that are not down for repairs or need supplies and are capable of conducting at least one of the assigned missions (even if not assigned at the time), is even worse—it is about 20 percent lower than that of the rest of the strategic mobility fleet.

It is significant that the C-5 reliability status is even below that of the C-141s, aircraft that are being currently phased out of the inventory. The impact of lower MCR and DR is that additional C-5s have to be committed as backup aircraft for vital peacetime missions, such as Presidential support flights.

The MCR is an important metric in identifying wartime capability in recent strategic airlift studies. In the MRS BURU, completed in 1995 for forces anticipated in the inventory in 2001, the average wartime MCR for C-5 was assumed to be 75 percent. It is currently below 65 percent and dropping, although presumably some scheduled maintenance actions could be deferred in wartime to bolster the MCR temporarily. In addition to the peacetime consequences of lower MCR, the wartime demands may be such that the U.S. Transportation Command cannot meet specified requirements for air delivery. This is an issue of growing concern.

In 1996 under contract to the U.S. Air Force San Antonio Air Logistics Center, Lockheed Martin Aeronautical Systems produced three studies[1] to identify and evaluate potential improvements in C-5 performance. The Phase I Study evaluated maintenance and logistics management practices and made recommendations to improve departure reliability. The Phase II Study evaluated the impact of the AMC Capital Investment Plan on C-5 departure reliability and mission capable rates. In both, modest improvements (few percent) were expected from the actions considered. The Phase III Study was less constrained and not tied to current logistics management practices or to specific well-identified and funded improvement programs. It introduced a comprehensive modernization package that promised to bring the C-5 to levels of departure reliability and mission capable rate near those of other airlifters in the fleet, such as the C-17 and KC-10.

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1 *C-5A/B Modernization Study, Phases I-III*, Lockheed Martin Aeronautical Systems, 1996, PROPRIETARY.

In July 1997, USTRANSCOM and Headquarters AMC asked IDA to make an independent examination of the data, methods, and conclusions reached in the Lockheed studies and to report its findings. IDA interviewed the Lockheed analysts, reviewed the documentation, and submitted a critique of the Lockheed report, published in two versions (proprietary[2] for government use only and redacted[3] for general use), in December 1997. Both the Lockheed Martin and IDA assessments identified upgrading and re-engining the C-5 as a cost-effective improvement, although the IDA analyses found less of an improvement in overall aircraft reliability than did Lockheed. Approximately $5 billion would be needed to perform the upgrades identified.

While upgrading the C-5 may be cost-effective if the C-5 is to be retained in the fleet, the larger question of whether money spent for improving strategic airlift should be directed toward C-5 improvements or toward some other improvements, such as adding more C-17s, was not addressed either in the Lockheed study or in the IDA critique thereof. That issue became the subject of the out- and oversize Analysis of Alternatives (AoA) conducted by HQ Air Mobility Command. The current document supplies the cost and reliability estimates for all the alternatives examined in the AoA.

2. MRS-05

The AoA is also supported by requirements data from another study. A new mobility requirements study, aimed at identifying mobility capabilities and requirements in the year 2005, is underway within the Joint Staff in the Pentagon. This study, named MRS-05, began in the fall of 1998. The final written report is due in late FY 2000. Among other assessments and recommendations, it will provide an update on strategic airlift requirements and will provide the authoritative basis for the AoA.

Although final results are not available at the time this report was written, it appears that the outsize and oversize airlift requirements will be higher than those from MRS BURU. Recent estimates by AMC put the total strategic airlift delivery requirement at about 33 percent more tonnage (out, over, and bulk combined) than used

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2 *Independent Analysis of C-5 Modernization Study,* IDA Paper P-3371, December 1997, UNCLASSIFIED/PROPRIETARY.

3 *Redacted Version of Independent Analysis of C-5 Modernization Study,* IDA Paper P-3454, December 1997, UNCLASSIFIED.

in MRS BURU. Thus a *lower limit* on requirements can be obtained from the MRS BURU results, with additional requirements expected upon completion of MRS-05.

MRS-05 assumes that forces are needed to support two Major Theater Wars (MTWs), as did MRS BURU, using a mix of sealift, airlift, and propositioning. The theaters of war are essentially identical to those analyzed earlier. MRS-05 extends its analyses beyond MRS BURU by planning to respond from forward deployed postures of engagement (POEs) to include intratheater as well as intertheater movement in a single unified study, to focus more on the impact of weapons of mass destruction (WMD), and to include host nation support (HNS). Warning time has also been reduced somewhat from MRS BURU assumptions. The time period for MRS-05 is 2005 at which time new programs not available in 2001 (MRS BURU) are appropriate.

3. Objective & Scope

The objective of this study is to assess the reliability and life cycle costs for all reasonable alternatives for improving strategic airlift capabilities. It does not address the operational effectiveness except through highly aggregate measures such as million ton-miles per day (MTM/D). The analyses conducted here are for AMC to use as a part of their Analysis of Alternatives of Outsize and Oversized Cargo Aircraft. AMC is conducting a separate analysis of the operational effectiveness of the alternatives in this report.

The analysis covers a time period that begins in FY 2000 and extends out to year 2040. The study excludes non-RERP costs already programmed for the C-5 and also excludes costs—acquisition or operating—for the programmed 135 C-17s (120 C-17s previously programmed plus 15 recently approve SOF C-17s). The operating costs of C-5s are considered, since several different configurations are considered, each with different O&S costs.

B. METHODOLOGY

The basic approach used in the analyses is the following:

1. Individual Aircraft
    - Identify aircraft to be used in alternatives
    - Estimate mission capable rates for these aircraft

2. Airlift Fleets

- Construct alternative fleets using capacity (MTM/D) as the metric
- Construct other alternative fleets as defined by AMC
- Conduct detailed cost assessments of the aircraft in each alternative, to generate life cycle costs for each alternative fleet through the year 2040.

Notice that the approach begins with individual aircraft (C-5 and C-17) but then turns to the fleets of which the individuals are members. Each area is discussed in greater detail next.

C. AIRCRAFT CONSIDERED

A number of aircraft configurations are considered in this study, although all are variants of the C-5 or C-17 because of the need to carry outsize and oversize cargo. New-design aircraft or lighter-than-air vehicles are not considered in this AoA because of the need to identify and act on near-term solutions that represent little, if any, research and development.

Three C-5 configurations are considered: Baseline, Full Upgrade, and a Partial Upgrade. None of these actually exist today, although the Baseline is a programmed C-5 configuration that will exist by 2005 and is closest to the current C-5. The other two are possible upgrade extensions of the Baseline configuration. A graphical depiction of these configurations and what they entail is seen in Figure 5, followed by a short description of each.

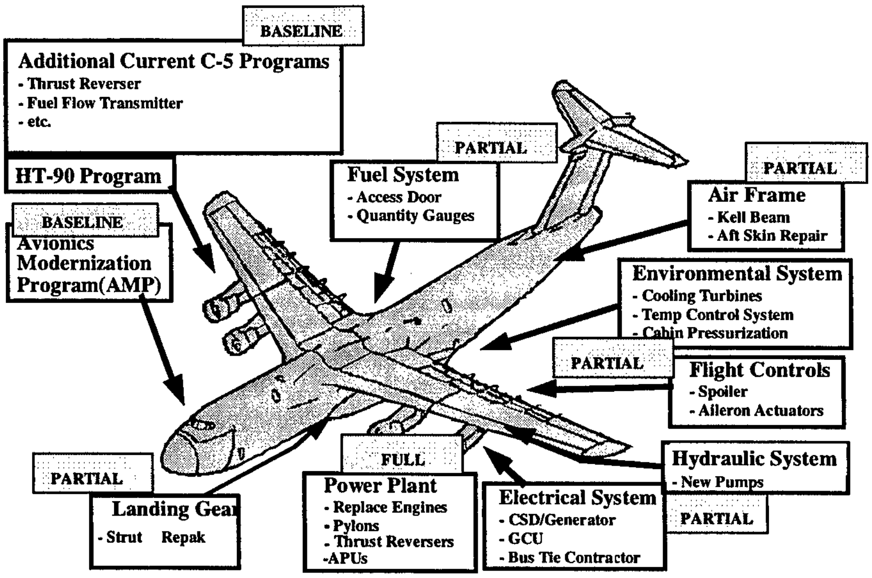

Figure 5. C-5 Configurations Analyzed

Baseline C-5. This is the C-5 as projected at the end of the current POM-supported improvements through 2005. The most significant improvements over the current C-5 will be in the Avionics Modernization Program (AMP), the installation of high-pressure turbine inserts (HT-90 program) to improve TF39 engine reliability, and a full overhaul of all thrust reversers.

Partial Upgrade C-5. This potential C-5 would build on the funded improvements in the Baseline and add specified improvements to the landing gear, the fuel system, flight controls, airframe, environmental system, hydraulic systems, and the electrical systems. Lockheed Martin identified these areas in their 1996 study as areas needing replacement in order to improve the mission capable rate. The Partial Upgrade does not include re-engining, but retains the Baseline TF39 engines with HT-90 and the thrust reverser overhaul. The reason for considering a Partial Upgrade is to introduce an alternative configuration to the Baseline but at lower acquisition cost relative to the Full Upgrade for which the engine costs dominate. It helps address the question of whether re-engining is needed.

Full Upgrade C-5. The Full Upgrade includes all improvements in the Partial Upgrade as well as more capable new engines to replace the TF39 engines. This was also a recommendation of the 1996 Lockheed Martin study that noted the low reliability of current TF39 engines.

The current TF39 engine produces approximately 40,000 pounds of thrust at sea level. The C-5 wing is designed to handle up to 50,000 pounds of thrust. The prevailing view within the USAF is that if re-engining is pursued, the new engines should take advantage of the availability of higher thrust engines and the inherent C-5 wing strength. There are 60,000-pound thrust engines in commercial use that can be de-rated to 50,000 pounds. There are also improved 40,000-pound class commercial and military engines (e.g., the C-17 uses 40,000-pound engines). If the de-rated 60,000-pound thrust engines were used on the C-5, the extra thrust would permit shorter takeoffs, if needed, and access to higher altitude trans-oceanic tracks. New 50,000-pound thrust engines are also coming on the market.

For this study we use a generic 60,000-pound thrust engine for costing purposes. It is not meant to represent any specific commercial engine but represents a suitable engine from that class. The new engines would be obtained through a competition, capitalizing on commercial engine experience instead of introducing a unique military design. The USAF is currently funding a program, the C-5 Reliability Enhancement and Re-engining Program (RERP), that is virtually identical to this full upgrade option.

Since the requirements for a re-engined C-5 are still being debated, for completeness we also assess the cost of replacing the TF39 with a modern more reliable but comparable thrust engine. Details on both of these engines can be found in Appendix B, Propulsion System Analysis, in Volume II (proprietary volume). We treat the lower thrust engine option as an excursion.

C-17. The C-17 considered in this study is identical to the planned production models, including the engine DO-3 upgrade. The new C-17 also introduces a center wing tank that provides additional fuel and longer legs for each mission.

Table 8 summarizes the basic C-5 and C-17 configurations considered in this study.

Table 8. Aircraft Configurations for Developing AoA Alternatives

Aircraft Class	Aircraft Configurations	Short Descriptions
C-5	Baseline	The baseline represents the configuration of the C-5 in 2005, including currently programmed upgrades.
	Partial Upgrade	The partial C-5 upgrade includes non-propulsion items that Lockheed Martin recommended replacing, as well as a few AMC-added improvements. The partial upgrade is not one of the final AoA configurations and is included as an excursion.
	Full Upgrade	The full C-5 upgrade includes the partial upgrade and adds replacement of the baseline propulsion system– engine, pylon, nacelle, and associated components.
C-17	Baseline	This study addresses only any additional aircraft beyond the 135 currently programmed for the Air Force, 15 of which are for SOF. All additional C-17s have the extended range fuel tank.

D. MISSION CAPABLE RATES

1. Approach

Aircraft MCR is used by the Air Force to describe the operational readiness of its aircraft fleets. The Air Force has three primary levels of readiness: full mission capable (FMC), partially mission capable (PMC), and not mission capable (NMC). An aircraft is mission capable if it is either FMC or PMC. The Minimum Essential Subsystems List (MESL) defines the systems and subsystems that must work for the aircraft to do its assigned missions.

The aircraft to which the MCR metric applies are those aircraft in the Primary Aircraft Inventory (PAI). Such aircraft are termed "possessed." This excludes Backup Aircraft Inventory (BAI), those aircraft currently "owned" by maintenance activities to perform scheduled or unscheduled maintenance, modifications, inspections, and repair. Thus, aircraft undergoing Program Depot Maintenance (PDM) or major modification using a depot field team are BAI and not possessed.

MCR combines failure frequency with repair efficiency and thus is dependent both on reliability and maintainability and supply. For example, if a part needed to repair a failed component is not available, then the resulting logistics or supply delay adds to the down time, over and above the time needed to replace the component once available. Therefore, component or subsystem repair times alone are not sufficient for modeling down time due to failure of the item.

No trouble found (NTF) actions do not generally trigger the supply system but do result in a NMC coding if the item is considered to be mission essential. Scheduled maintenance activities on possessed aircraft also result in a NMC status. Typically, the C-5 aircraft undergoes periodic Home Station (HS) checks and isochronal inspections. Since the aircraft remains in a possessed status during such scheduled maintenance, it is recorded as NMC over the maintenance period.

As indicated above, an aircraft can be in a not-mission-capable status for a number of causes. Listed below are the NMC categories used in this study.

- Failures—This category represents the downtime resulting from failures of critical components or subsystems. It is the primary cause of not-mission-capable times and is the NMCR component for which the simulation model was developed.
- Isochronal Inspections—This is a scheduled maintenance activity performed at the operating base approximately every 400 days and is designed to keep the aircraft healthy and safe.
- Home Station Checks—This is also a scheduled maintenance activity performed every 90 days and is also done to ensure the aircraft is healthy and safe.
- Other Non-Corrective Maintenance—These are generally inspections and maintenance activities that are performed to meet special conditions or emergencies and that have not been included in the other non-corrective maintenance schedules. An example might be discovery of a serious safety problem such as a crack in a plane resulting in a directive to inspect all aircraft that may be subject to the same problem.
- Refurbishments—These are activities performed on base to maintain the aircraft in an operable state. They might include such activities as washing, painting, and minor corrosion repair.
- Cannibalization—Typically, for the C-5 fleet there is a "cann bird" at each major C-5 operating base that acts as a source of parts supply. A part needed to restore an aircraft to mission capable status after returning from a mission is borrowed from the cann bird if it is not available from supply. When the part is received through the logistics supply chain at the base, it is used to fill in the hole in the cann bird. During such time that the cann bird has missing critical parts, it is not mission capable.

The MCRs of current C-5s and C-17s are known. The data are maintained in USAF GO-81 and REMIS files. In fact, it is because of the poor reliability of the current C-5 and the need to recommend solutions that this study comparing alternatives is being done.

For this study, we need to estimate the reliabilities of aircraft that do not yet exist, namely the various upgraded versions of the C-5 as well as an improved C-17 with center wing tanks. To this end, IDA has devised a simulation approach to estimating aircraft MCR by considering contributions from individual systems that are to be replaced. This model was introduced in the cited 1997 IDA report but was improved considerably for this study.

The model explicitly takes into account the phenomenon that more than one failure can occur during a flight, although typically only one—the pacing item—is cited as the cause of failure. Figure 6 shows schematically the sequence of events modeled, including the potential for "masking" of one failure by the pacing item failure. By calibrating the single parameter in the results to current C-5s, new configuration C-5 MCR can also be estimated once the particular parts and the associated reliabilities are substituted for current values. Flying hours play a dominant role in the failure rate estimates in Step 2 in the process, although specific items known to fail only on takeoff and landing (landing gears, tires) are treated on a per-sortie basis.

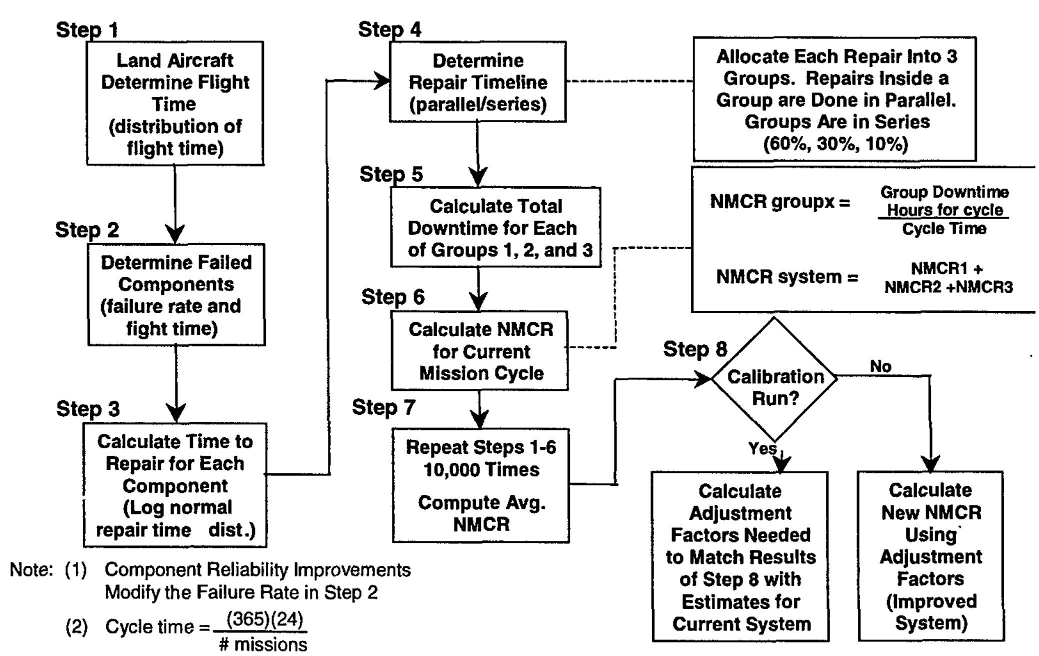

Table 9 summarizes the data sources used in constructing contributions to MCR for the model. The primary types of data needed are

(1) Number of flying hours per year for the C-5A and B models and the size of the fleet possessed during that year

(2) Component-level reliability and failure rates

(3) Maintainability in terms of hours required to replace failed components

(4) Number of Type 6 actions recorded, i.e., events in which no problem could be found but for which the aircraft was grounded anyway

(5) Extent to which multiple repairs can be conducted simultaneously or sequentially.

Table 9. Summary of Major Types of Data Used in the MCR Model

Data Type	Primary Source	Description	Period	Use
Flying Hour and Fleet Sizes	AMC - Flying hour program and actual experience captured in C-5 historical data bases	Number of Total Authorized Inventory (TAI) and Primary Authorized Aircraft (PAA) and total number of flying hours per year by aircraft type and component	1996-1998	Develops sortie duration and mission cycle parameters
Reliability	G081/REMIS and C-5 historical data bases	Failure rates at the 3-digit work unit code (WUC) level	1996-1998	Determines failure probability of subsystems
Maintainability	G081/REMIS and C-5 Historical data bases	Maintenance man-hours per action at the three digit WUC level	1996-1998	Determines downtime after adjustment to reflect mean time to repair
Type 6 Actions	G081/REMIS	Frequency of No Trouble Found actions (NTF)	1996-1998	Adjusts reliability improvements to reflect various types of maintenance activities
Parallel/Sequential Repair Probability	AMC/LGAA	The probability that a component in the failure group cannot be repaired while other repairs are taking place	NA	Adjusts binning (parallel repair) operations

We do not model every single component, only the items listed in the USAF Minimum Essential Subsystem List (MESL). To estimate the increase in MCR once items are replaced to attain the Baseline C-5 from current system or to attain either a Partial or Full Upgrade to the C-5, we generally used Lockheed Martin engineering estimates of failure rates at the three-digit work unit code (WUC) level. In a few cases we used our own improvement rate estimates. We did not change maintenance times for components once they fail.

2. Results

Table 10 summarizes the MCR results for the various C-5 configurations and for the C-17. Note that three columns of results are shown: Peacetime MCR, Surge MCR, and Sustained MCR.

Table 10. Summary of Mission Capable Rate Results

Configuration	Aircraft	Mission Capable Rate (%)		
		Peacetime	Surge	Sustain
Current w/o Letter Check	C-5A	57.7	66.6	59.7
	C-5B	68.4	76.0	70.4
	Fleet Avg	61.9	70.3	63.9
Current w/ Letter Check	C-5A	63.1	66.6	64.2
	C-5B	72.9	76.0	73.0
	Fleet Avg	67.0	70.3	67.7
Baseline w/o Letter Check	C-5A	57.8	66.7	59.8
	C-5B	68.7	76.1	70.5
	Fleet Avg	62.1	70.4	64.0
Baseline w/ Letter Check	C-5A	63.2	66.7	64.3
	C-5B	73.2	76.1	73.1
	Fleet Avg	67.2	70.4	67.8
Partial Upgrade w/ Letter Check and Increase Supply Support	C-5A	66.9	72.1	69.7
	C-5B	76.1	79.2	76.2
	Fleet Avg	70.6	74.9	72.3
Full Upgrade w/ Letter Check and Increased Supply Support	C-5A	70.1	75.8	73.4
	C-5B	78.8	81.9	78.9
	Fleet Avg	73.5	78.2	75.6
C-17	Fleet Avg	85	90.0	87.5

3. MCR Sensitivity Analyses

We also conducted sensitivity analyses as part of a validation procedure for the MCR model. The analyses exercised the MCR model to test its behavior and sensitivity to assumptions different than those made here. The model behaved as expected throughout its parameter space and gave nearly identical results for any different set of assumptions, provided that the model was always calibrated to current C-5 reliabilities.

The verification and validation of the model was performed by a series of executions of the MCR model using different parameter values. Because a huge number of combinations of parameters and corresponding values exist, the testing was not exhaustive. The purpose of the testing was (1) to ensure that sufficient iterations had been conducted for stability in the solutions, (2) to determine if the model behaves as expected when parameters are changed, and (3) to test the sensitivity of the results to some of the more arbitrary parameter values.

Any assumption of the model will influence the fidelity of the results to some degree. Therefore, the implicit and explicit assumptions of the model, as well as any implied constraints that are a consequence of these assumptions, were also examined as part of the verification and validation (V&V) process.

a. Number of Trials

We first examine the impact of number of trials on results. For the MCR model, there is a tradeoff between the accuracy of the simulation and the required computational time. Therefore, the effect of the number of Monte Carlo trials on the MCR model results was investigated to determine the number of trials required for an accurate simulation. Figure 7 shows the results of this assessment for two different C-5 configurations considered. There we plot NMCR versus the number of trials. From Figure 7 we conclude that 10,000 iterations are sufficient to achieve a stable solution. There is no advantage in proceeding to 25,000, but at least 10,000 are needed for confidence in the results. All our results shown in this paper use 10,000 Monte Carlo replications.

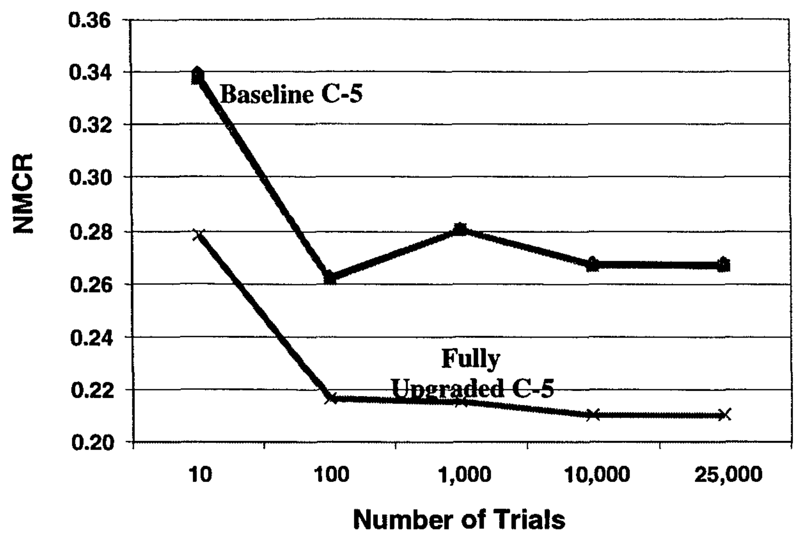

Figure 7. Effect of Monte Carlo Trials on NMCR Model Results

b. Effect of Assumptions on Repair Bin Probability

The model treats multiple repairs in terms of separate "bins." A bin represents a set of repairs that are worked on concurrently. The pacing item with the longest repair time determines the time required per bin. When multiple failures occur, manpower and facility constraints dictate that some repairs will be done serially in separate sequential repair bins rather than concurrently. The model assumes that in peacetime, three concurrent bins are used in sequential order; during surge times the MCR model uses two concurrent bins in sequential order. The bin where a failed part is repaired is determined by a random draw for each Monte Carlo iteration. In peacetime 60 percent of failures are repaired concurrently in bin 1, then move to bin 2 for 30 percent of repairs, and finally bin 3 completes the remaining 10 percent. During surge times, only two bins are used in which 90 percent of failures are repaired in bin 1 and 10 percent in bin 2.

These percentages seem reasonable but are admittedly somewhat arbitrary. We could find no data from which to make these assignments, so in collaboration with logistics experts within AMC, we made best guesses. The question arises as to the sensitivity of the results to different sorting assumptions. Does the MCR depend on the binning assumption? The answer turns out fortunately to be *no*. As long as the model results are calibrated against current data for a given assumption about the relative percent of actions in the bins, the results for upgraded aircraft are relatively insensitive to the allocation assumptions. Calibration restores integrity to the problem.

For example, if the model is calibrated for the current C-5 for each separate bin 1 probability, Figure 8 shows results for NMCR for the three C-5 configurations under different assumptions about binning for surge conditions for which there are two bins. The x-axis shows the probability that a failed component ends up in bin 1; the probability of being in bin 2 is 1 minus the x-axis value. The line labeled "Current C-5" is always a constant by construction, since it always is calibrated to give the same result. The Baseline C-5, with AMP and HT-90 programmed improvements, is essentially identical to the current C-5 in these calculations. The different calibration factors obtained from this exercise are applied for the appropriate binning assumption to the other configurations. Figure 10 illustrates that there is little change in the model NMCR results over a large range of binning assumptions. This indicates that as long as the model is calibrated to historical data, the relative impact of modernization to the C-5 NMCR is insensitive to the bin probabilities (except for end effects with probability nearing unity), and therefore this parameter is not a major driver of the model results.

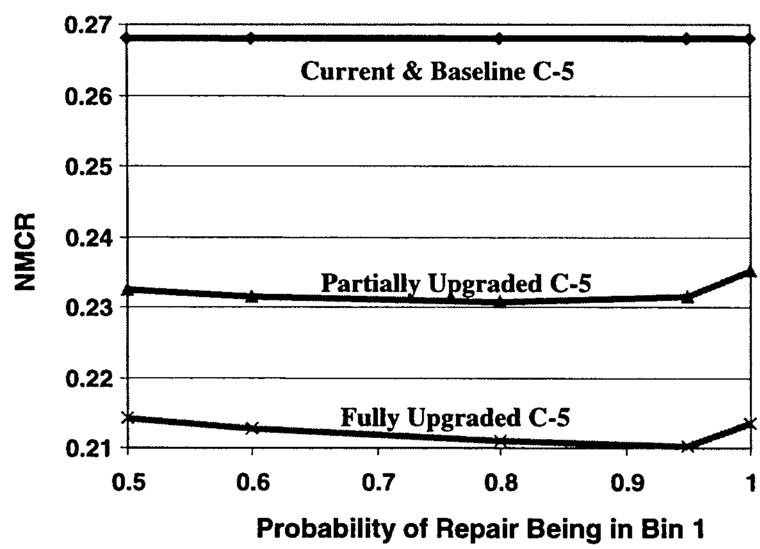

Figure 8. Effect of Repair Bin Probability on MCR Model Results

c. Effect of Type 6 Repair Rates

The G081 data base lists the type and number of failures for each part of the C-5. The failures are categorized into six types. A Type 6 failure occurs when the pilot suspects a failure or the diagnostic electronics indicate that a part needs repair.

Discussions with USAF personnel indicated that the Type 6 repair rate may be overstated. Thus, there is some uncertainty about the correctness of the Type 6 reports. For that reason we examine how sensitive results are to changes in assumption about Type 6 failures.

For our basic assumption we assume that one-half of the reported Type 6 failures result in a repair action. The other half constitute "no fault found." We have varied the probability that a Type 6 report results in an actual repair action as a sensitivity excursion. We refer to the probability that a reported Type 6 failure results in a downtime and repair as the "Type 6 repair weight." As expected, Figures 9 and 10 illustrate that as the Type 6 repair weight increases, the number of failures and NMCR also increase in a nearly linear fashion. This shows the model performs as expected when a parameter is changed. In these figures, the basic assumption of 0.5 is shown for reference purposes.

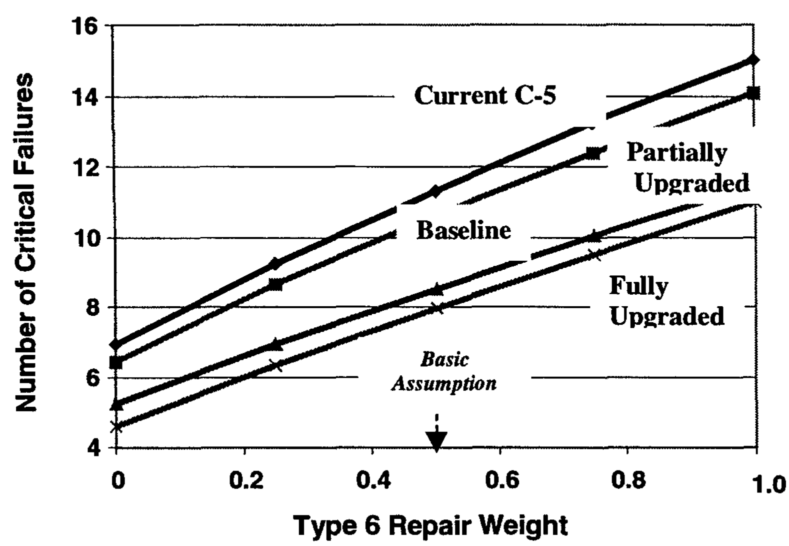

Figure 9. Effect of Type 6 Repair Weight on Number of Critical Failures

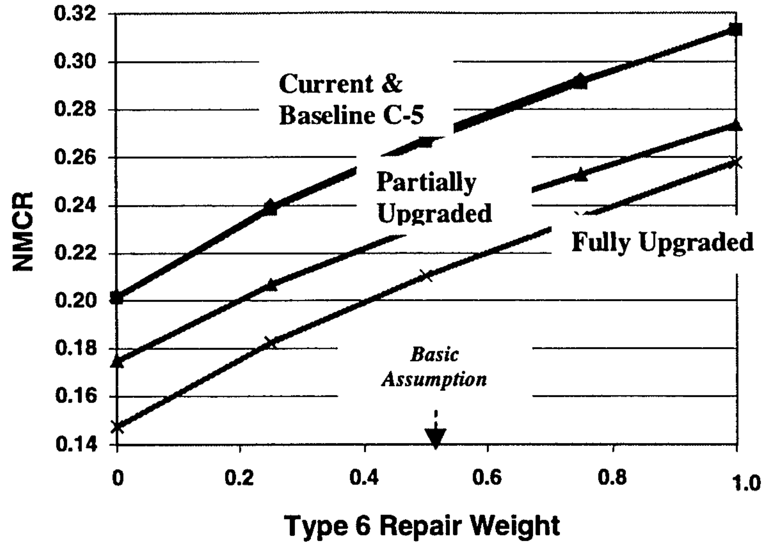

Figure 10. Effect of Type 6 Repair Weight on MCR Model Results

If the model is calibrated for the current C-5 for each separate repair weight, Figure 11 illustrates little change in the results of the MCR model. This indicates again that as long as the model is calibrated to historical data for current aircraft, the relative impact of modernization to the C-5 NMCR is fairly insensitive to the Type 6 repair weight, and therefore this parameter is not a major driver of the model results.

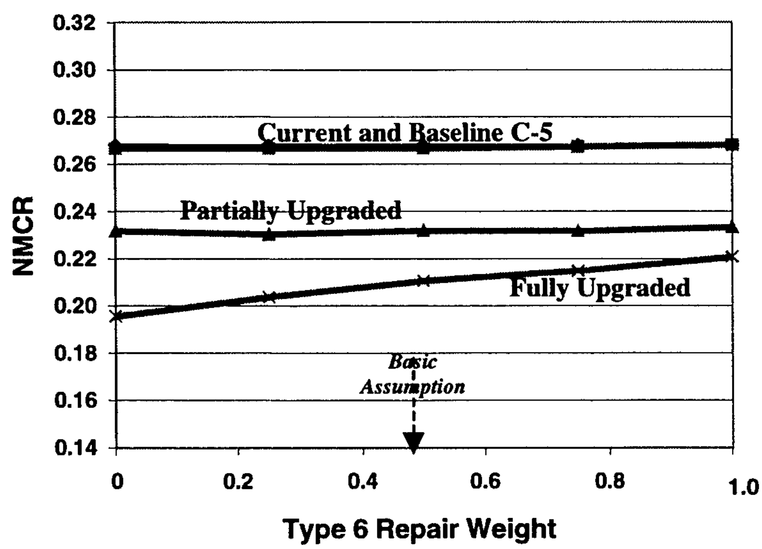

Figure 11. Effect of Type 6 Repair Weight on MCR Model Results

We conclude from these analyses and others in Part 3 (Analyses) that the MCR model behaves as expected and provides results that are not strongly dependent on certain of the more arbitrary assumptions. This provides greater confidence in the outcomes.

4. Additional MCR Improvements

Does the USAF want to consider improvements other than those Lockheed Martin proposed for incorporation into the Full Upgrade for the C-5? The MCR model was also used to determine potential C-5 items that could be modernized to reduce the NMCR further than was proposed even for the Full Upgrade. Cost of modernization was not considered when determining potential parts required for modernization. The top 10 identified items are shown in Table 11. The most significant reduction in NMCR is ranked number 1 in Table 10: the fuel tank, part of the fuel system. The next most important reduction are the flaps, part of the flight controls system, etc.

Table 11. Additional Modernization Items to Improve MCR

Rank	Part	System	Description
1	46A	Fuel System	Fuel Tank
2	14J	Flight Controls	Flaps
3	46B	Fuel System	Fuel Pump
4	14L	Flight Controls	Slat Assembly
5	11B	Air Frame	Visor Door
6	13L	Landing Gear	Wheel and Tires
7	14A	Flight Controls	Aileron and Flt Spoilers
8	41A	Aircon, Pressuriz, Deice	Aircon, Pressuiz, Deice
9	46H	Fuel System	Fueling/Defueling Sys
10	13B	Landing Gear	Nose Landing Gear

To estimate further modernization, we reduced the failure rate of the modernized part by 90 percent but kept downtime the same. The relative reduction of NMCR for each part being modernized is shown in Figure 12. The results are cumulative, in the sense that each improvement included all improvements to its left. MCR model results indicate that if all 10 items were modernized, the C-5 NMCR can be reduced by as much as 24 percent below that achievable in the Full Upgrade.

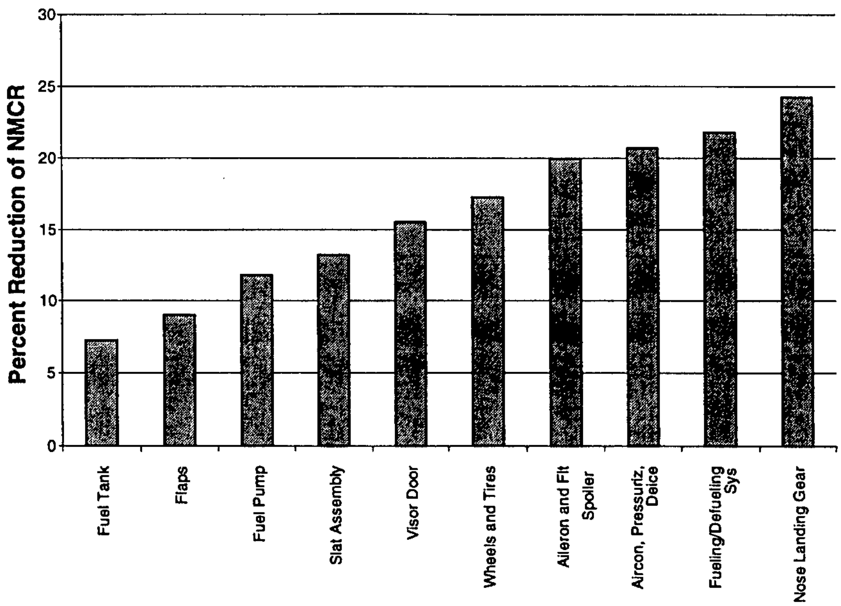

Figure 12. Impact of Additional Modernization on NMCR

E. ALTERNATIVES

Analysts at AMC/XPY took the MCR values and constructed fleets that initially had comparable MTM/D values. In ensuing analyses, AMC later changed the alternatives to be examined to the ones in Table 12 All the alternatives except 1, 3, 5, and 7 have comparable MTM/D for out- and oversize cargo.

Table 12. AoA Alternatives Used for Life Cycle Costing

Alternative	C-5A	C-5B	Additional C-17 Aircraft Beyond 135	MTM/D
1	Baseline	Baseline	None	24.9
2	Baseline	Baseline	20	27.1
3	Baseline	Baseline	45	30.1
4	Baseline	Full upgrade	20	27.8
5	Baseline	Full upgrade	45	30.7
6	Full upgrade	Full upgrade	None	27.2
7	Full upgrade	Full upgrade	45	32.3
8	None	Full upgrade	75	27.7
9	None	None	132	27.9

The following points are provided for clarification. The additional C-17 aircraft for Alternatives 2, 4, 8, and 9 are based on HQ AMC's estimate of what would be needed to meet a minimum MTM/D requirement for outsize and oversize airlift. They estimate that all these alternatives supply about 27.1 MTM/D except for Alternative 1, with Baseline C-5s and no additional C-17s. Alternative 1 provides 24.9 MTM/D. A constraint for full squadron implementation was imposed for the smaller increment, thus Alternatives 2 and 4 have the same 20 additional C-17s. The 45 additional aircraft for Alternatives 3, 5, and 7 were developed by considering a Boeing proposal to provide 60 additional aircraft beyond the planned 120, 15 of which are assumed to be designated for the SOF fleet.

In addition, we have analyzed a number of other alternatives. These include partially upgraded C-5s as well as alternatives with different numbers of C-17s than shown in Table 12. We have also analyzed the nine alternatives listed with different assumptions about flying hours and the nature of the engine involved in the upgrade. All are treated in Volume II and some are included in the sensitivity analyses of this volume.

F. COST ANALYSES

Based on available data, we have estimated the costs and associated schedules to acquire each of the alternative aircraft configurations and to operate them until 2040. Relevant costs include those incurred to procure new C-17 aircraft in the extended range configuration (center wing tank), to modify existing C-5 aircraft, to operate and maintain the aircraft through FY 2040, and to dispose of or recoup residual value at the end of the life cycle period in 2040. Costs estimates were developed using available procurement data, information from historical studies, service estimates, and independent IDA assessments, as appropriate. Specific tools used to estimate the various LCC components and to develop schedules include cost estimating relationships, analogies, and bottom-up analyses.

In this section we summarize the costing approach and results. In Section G, we combine cost details for individual aircraft into LCC estimates for the alternatives.

1. Acquisition/Investment Costs

The acquisition and investment costs developed here represent marginal or incremental costs incurred to acquire the C-5 aircraft modifications and new C-17 aircraft. These costs include

- Research, development, test, and evaluation (RDT&E) [limited to engineering and manufacturing development (EMD)]
- Procurement (nonrecurring, recurring flyaway costs which are adjusted for quantities using buy quantities and improvement curves, support investment, initial spares and spares lay-in to support the C-5 letter check maintenance concept)
- Military construction (MILCON).

We discuss here the methodology and results for the C-5 modernization acquisition cost estimates, followed by those for the C-17.

a. C-5 Acquisition

The C-5A/B acquisition costs are for the configurations defined earlier in this paper. The C-5A/B acquisition costs are further split into costs to provide a partial upgrade and full upgrade of both the C-5A and C-5B aircraft. A partial upgrade includes all structural and other-than-propulsion-systems modifications proposed by the Air Force, plus replacement of a portion of the C-5A upper crown skin. The full upgrade includes all partial upgrades plus a new propulsion system. The C-5A/B Avionics Modernization Program is under contract and is considered a sunk cost for this study.

Data Sources. Sources of data used to make cost estimates of C-5 upgrades are the Air Force Program Offices (Wright Patterson AFB and Warner Robins AFB), Air Material Command, Lockheed Martin, Pratt & Whitney, General Electric, and Rolls Royce.

Schedules. The schedules used for developing and procuring the C-5 upgrades are as follows:

- EMD—Engineering and Manufacturing Development is assumed to start in FY 2000 for the C-5 alternatives.
- Procurement—Modification rate for C-5 aircraft begins with 6 aircraft in FY 2003, 12 in FY 2004 and reaches a steady-state rate of 18 per year thereafter. Costs for long lead procurement items start in FY 2002.

C-5 Upgrade Costs. We assume that the baseline aircraft upgrade costs in the Air Force Program P3X Report–FY2000 Budget Estimate Submission (BES) are costs. Since they are funded through the POM years, they are common to all alternatives. Upgrades include C-5 Program Office estimates for the Malfunction Detection, Analysis and Recording Subsystem (MADARS) replacement. For EMD cost estimates, the KC-135R cost experience was used, adjusted by cost estimates for the C-5 RERP and other data provided by Lockheed Martin. We estimated the remaining systems using information that Lockheed Martin provided and that was derived to a large measure from their C-5D proposal. We also included additional AMC recommended improvements: flap and slat upgrades or overhauls, cabin pressurization seal replacements, and fuel boost pump wiring replacements. As a result of our assessment of the structural life of the C-5A, we also included $2.5 million per C-5A for replacing a segment of the C-5A upper crown skin. For the C-5A aircraft, we included estimates for Government testing and management of the program and added estimates for simulator costs, based on information we received from HQ AMC.

Table 13 displays the C-5 upgrade acquisition costs for all upgrades in FY 2000 constant dollars. The first column shows cost estimates for EMD, a number independent of how many C-5s will ultimately be upgraded. The second is the flyaway cost for 126 C-5s. The fourth is the cost of initial support investment and spares. An additional $80 million to implement letter check was included in support investment and spares. These costs are for the lay-in of initial spare parts used to support the aircraft-level letter check maintenance concept in lieu of the current aircraft maintenance concept based on isochronal inspections, refurbishment, and Programmed Depot Maintenance. EMD and procurement estimates for ensuring structural integrity, replacing auxiliary power units, and the systems upgrades are based on Lockheed Martin's data, adjusted for production rate of 12 to 18 modifications per year. All other cost elements are based on either historical factors or analogous systems cost. The last column is the cost of all 126 C-5s for each upgrade category.

Table 13. Acquisition Cost for C-5 Upgrades
FY 2000 Dollars in Millions

EMD Estimate			
Cost Element	**Engine**	**Airframe & Systems**	**Total**
Subtotal Contractor Costs	$420.5	$321.4	$741.9
Program Office Mission Support	$8.4	$6.4	$14.8
Government Flight Test	$14.2	$10.8	$25.0
Total EMD	$443.0	$338.7	$781.7
Procurement Estimate			
Cost Element	**A Fleet**	**B Fleet**	**A/B Fleet**
Total Full Upgrade Procurement	$3,053.2	$1,884.0	$4,927.3
Full Upgrade Procurement Unit Cost	$40.7	$38.4	$39.7
Total Costs for Acquisition			$5,709.9

The single largest cost upgrade is the powerplant (engine) replacement. From this table, we see that the re-engining of the entire C-5 fleet is estimated to cost $4.9 billion, relative to the total upgrade cost estimate of $5.7 billion.

b. C-17 Acquisition Costs

This section discusses the methodology used for estimating the acquisition costs for C-17 in the extended range configuration and the results of the cost analyses. The extended range version includes configuration changes to install a center wing tank. Acquisition costs for the C-17 reflect both procurement and MILCON resource requirements. EMD is complete for the existing configuration of the aircraft; for the extended range version, EMD is scheduled to be complete in time to allow production incorporation at aircraft number 79.

Data Sources. Sources of data used to make cost estimates for buying new C-17s are the C-17 System Program Office (SPO) at Wright Patterson AFB, the Boeing Company, and Pratt & Whitney.

Schedules. The assumptions used for developing and procuring new C-17 aircraft for the airlift fleet are as follows:

- EMD—There is no C-17 EMD. Non-recurring development costs for the current and extended range versions are assumed to be funded (sunk costs), with development completed before purchase of additional aircraft considered in the AoA alternatives.

- Procurement—The last 5 of the 120 aircraft currently under contract are scheduled to be procured in FY 2003. Assuming a maximum production rate of 15 aircraft per year, this would allow 10 additional aircraft to be procured in FY 2003 and 15 per year thereafter. We assumed that the USAF would buy 10 of the 15 additional SOF aircraft in FY 2003 and the remainder in FY 2004. Given this assumption, *no* additional dedicated strategic airlift can be bought in FY 2003 and a maximum of 11 C-17s can be bought in FY 2004. The production rate is assumed to be at 15 per year thereafter.

C-17 Cost Estimates. We used a top-down approach via historical cost data from Boeing and C-17 SPO budget estimates as the basis for costing additional aircraft. This has proved contentious, since the costs obtained in this fashion are at variance with recent Boeing proposals. These are discussed next.

We used the aggregate airframe, engine, and avionics cost data at the flyaway cost level provided in the C-17 SPO 1537 budget sheets. We compared the budget data with the information provided by Boeing and assessed that the 1537 data were sufficiently accurate to be used to project the costs of follow-on C-17 procurements. To estimate the cost of future procurements, we conducted a regression analysis using the actual cost of the first 48 and the budget projections for the remaining 72 to complete the 120 C-17 aircraft program. This regression curve, when extrapolated, served as the basis for our estimates of the cost of any C-17s procured beyond the programmed 120.

As noted, there are other viewpoints. Boeing and the C-17 SPO have performed several studies with the objective of reducing the C-17 manufacturing costs. Recently, Boeing and the SPO have defined potential Cost Reduction Initiatives (CRIs) to achieve a "must cost" goal for aircraft procured beyond 120. These CRIs are to be implemented starting with the 49th aircraft. In March 1999, using the CRIs as the basis, Boeing proposed selling an additional 60 aircraft to the Air Force for $149 million apiece, which translates into $151 million in FY 2000 dollars, and significantly below current prices.

Table 14 compares the two average acquisition costs for each of the next 60 aircraft.[4] The first uses our regressions as a basis for projecting the costs for the follow-on aircraft. The second is based on Boeing's proposal for the next 60 aircraft. The flyaway cost includes the airframe, engine, and avionics costs, as well as the cost for the center-wing fuel tank and product improvement and non-recurring costs. All costs below the recurring flyaway in Table 14 are based on factors derived from C-17 historical cost data in the Air Force's 1537 budget sheets. HQ AMC provided the cost estimates for 5 additional flight simulators and for MILCON. The average cost is $2 million per C-17.

4 Additional detail can be found in Volume II, along with an intermediate case that uses the Boeing proposal and makes adjustments for recent management reorganization. Its cost lies intermediate between the two cases shown in Table 14 .

Table 14. C-17 Acquisition Unit Cost Estimates for 60 Aircraft Beyond 120

Cost Element	Average Unit Acquisition Cost (in FY 2000 $M)	
	Extrapolated from USAF 1537 Budget Data	Boeing Proposal (adjusted for inflation)
Flyaway Cost (recurring & non-recurring)	196	156
Investment Spares & Support	23	17
Simulators & MILCON	2	2
Total Unit Acquisition Cost	**221**	**175**

The right column in Table 14 summarizes costs from the Boeing proposal, adjusted for inflation and with $5 million in product improvement and non-recurring costs added. The proposal itself includes the cost for the center-wing fuel tank. The remaining budget cost items employ the same percentages and the same simulator and MILCON estimates as the first estimate to arrive at total acquisition cost. The average cost is $175 million per C-17, about 20 percent lower than our estimate.

2. O&S Cost

Operating costs accumulate through FY 2040 to such an extent that they dominate cost comparisons. We explain our approaches in this section.

The O&S costs developed here represent the marginal or incremental costs incurred to operate and support the C-5 and C-17 aircraft configurations in defined fleet compositions for each alternative over the assessment period. In estimating O&S costs, the general approach was to use the cost element structure defined in the Operating and Support Cost Estimating Guide published by the Office of Secretary of Defense Cost Analysis and Improvement Group (CAIG) dated May 1992. The cost element structure is provided in Table 15.

Table 15. O&S Cost Element Structure

Mission Personnel
Operations
Maintenance
Other
Unit-Level Consumption
Petroleum, Oil & Lubricants (POL)
Consumables
Depot-Level Repairables
Other
Depot Maintenance
Airframe Overhaul
Engine Overhaul
Other
Contractor Support
Sustaining Support
▪ Support Equipment Replacement
▪ Modification Kit Procurement/Installation
▪ Sustaining Engineering
▪ Post-Deployment Software Support
▪ Simulator Operations
Indirect Support
▪ Personnel Support
▪ Installation Support

In the study, we used a combination of standard models and tailored methods to estimate the cost elements.

Tailored O&S assessment methodologies were developed to estimate the costs of the following: propulsion subsystem, aircraft structure maintenance, and C-5 reliability and maintainability improvements other than the propulsion system. Where a tailored assessment methodology was not used, the Air Force CORE model and factors and cost information available in Air Force Instruction (AFI) 65-503 and Air Forces Total Ownership Cost (AFTOC) were used as the basis from which estimates for other costs were derived. The AFI 65-503 does not include cost or factors for estimating sustaining engineering and software support. Using information from AFTOC and budget data from AMC, we estimated costs for these elements. We also made assessments to understand the effects on manpower and aircraft maintenance costs as the results of the C-5 improvements. In addition, we assessed the effects of changes to an annual letter check as the scheduled aircraft maintenance in lieu of isochronal inspections and refurbishment at the base level and PDM at the depot.

For the C-17, we assessed the critical costs using tailored methods for contractor logistics support (CLS), structures, reserve component staffing, and the propulsion system. The CLS costs were derived using actual and estimated Flexible Sustainment costs provided by Boeing and the C-17 Program Office. Boeing projections were compared to current Flexible Sustainment experience and adjusted for anticipated increases in aircraft depot maintenance costs to keep the aircraft healthy through FY 2040. The adjusted flexible sustainment costs were estimated as CLS costs per flying hour and included in the CORE model estimates. We estimated engine maintenance costs using the same methodology as that used for the C-5 propulsion system.

A summary overview of the methods used for estimating O&S costs for the C-5 and C-17 are provided in Table 16.

Table 16. Methodology for Different O&S Categories

Cost Element	CORE Model	Propulsion Estimates	Other C-5 Improvements	C – 5 Structures	C-17 CLS	C-17 Structures
Mission Personnel						
- Operations	•					
- Maintenance	•					
Unit-Level Consumption						
- POL		•				
- Consumables	C-17 common	•	•		•	
- Depot-Level Reparables	C-17 common	•	•		•	
Depot Maintenance						
- Airframe Overhaul	•			•	•	•
- Engine Overhaul		•				
Contractor Support					•	
Sustaining Support						
- Support Equipment Replacement			•		•	
- Modification Kit Procurement/ Installation	•					
- Sustaining Engineering	C-5				•	
- Post Deployment Software Support	C-5				•	
- Simulator Operations	•				•	
Indirect Support						
- Personnel Support	•					
- Installation Support	•					

a. C-5 Operating and Support Costs

We summarize first the O&S cost estimate for flying hour failure-related elements and support equipment elements. Next we treat the propulsion system O&S. Finally, we assess other cost elements in the CORE model. Details can be found in Volume II, Appendix A.

C-5 Flying Hour Failure Related and Support Equipment O&S Estimates. This section deals with the costs of Bulk Supply (GSD), Consumable Parts and Depot Level Reparables (MSD), and Support Equipment Replacement (SE) for the various C-5 configurations defined in the alternatives, *with the exception* of costs in these categories that are associated with engines. Engine O&S costs are addressed separately.

The methodology used to develop our estimate entailed

- Developing a C-5 baseline cost for these items
- Evaluating projected reliability improvements associated with proposed upgrades
- Assessing the cost per flying hour (CPH) savings resulting from improved reliability
- Calculating the upgraded C-5A and the C-5B cost for these same items
- Phasing the costs to account for the different implementation schedules associated with the various alternatives.

C-5 Baseline Cost. The C-5 baseline costs were developed using cost data provided by the USAF Cost and Economic Analysis Agency (AFCEAA) and using Primary Authorized Aircraft (PAA), Total Authorized Inventory (TAI), and flying hour data provided by AMC. The cost data sources consisted of a number of Excel spreadsheets containing CPH and cost per aircraft (CPA) for various cost categories by Major Command (MAJCOM) and aircraft type (MDS) for combinations of years ranging from 1999 through 2006. The AMC PAA, TAI, and flying hour data were organized in a similar fashion.

The analyses are lengthy and involve judgments about different data sources. Details can be found in Volume II, Appendix A. In Table 17 we summarize our calculation of the non-engine cost baseline, the baseline we deal with in this section.

Table 17. Non-Engine Baseline

		Non Engine Percent		Non Engine CPH/CPA	
Item	Total CPH/CPA ($)	C-5A (%)	C-5B (%)	C-5A ($)	C-5B ($)
GSD	918	87.56	88.93	804	816
MSD	2,852	90.05	88.41	2,568	2,522
SE	138,565	87.56	88.93	121,328	123,225

Reliability Improvements. As already mentioned, we estimate the current cost savings associated with proposed C-5 improvements using data on reliability improvements that were generated in our earlier C-5 analysis. It is appropriate, therefore, to briefly review how these data were derived.

Lockheed engineers made estimates of reliability improvements in terms of inherent failure rates. In most cases, there was reasonable rationale or data, but for several, the major justification was "engineering judgment." We made several adjustments to the initial reliability improvements, supplying our own engineering judgment as necessary. In addition, we noted that the improvements were tied to only the inherent maintenance event (IME) (failure) rates. After examining detailed data provided to us by the Air Force, we found a considerable amount of Type 6 or induced failures, those caused by failure of other items or caused by maintenance. Applying a methodology that used the actual ratio of induced to total failures for the item being modified (excluding engines), we adjusted the Lockheed improvement factor for each of the items being upgraded. The results of these adjustments, in terms of saved maintenance man hours (MMH) and IME are summarized in Tables 18 (for C-5A) and 19 (for C-5B).

Table 18. C-5A Savings in MMH and IME Resulting from Reliability Improvements

MMH/1000 FH [a]			IME/1000 FH [b]		
Pre-Upgrade	Savings	Post-Upgrade	Pre-Upgrade	Savings	Post-Upgrade
3995	2297	1698	376	226	150

[a] Maintenance man hours per 1,000 flying hours

[b] Inherent maintenance event per 1,000 flying hours

Table 19. C-5B Savings in MMH and IME Resulting from Reliability Improvements

MMH/1000 FH [a]			IME/1000 FH [b]		
Pre-Upgrade	Savings	Post-Upgrade	Pre-Upgrade	Savings	Post-Upgrade
1788	1190	598	152	103	48

[a] Maintenance man hours per 1,000 flying hours

[b] Inherent maintenance event per 1,000 flying hours

We have broken the savings down into two categories: Other Improvements, and Other Engine Improvements. The reason being that there are two upgrade alternatives: a full upgrade that includes engines, and a partial upgrade that does not include engines.

Although we have stressed that the engine upgrade *per se* is being treated separately, certain items in this section, e.g., pylons, will only be upgraded if the engine itself is replaced. In the case of the full upgrade, we use the total savings in MMH and IME to adjust CPH and CPA; however, in the case of the partial upgrade we use only those MMH and IME savings associated with the category "Other Improvements."

In Table 20 we show the estimated annual "Other O&S" cost for each C-5A PAA aircraft under either upgrade option (full or partial).

Table 20. C-5A Cost per PAA Aircraft Flying 438 Hours Annually

	Full Upgrade ($)			Partial Upgrade ($)		
Cost	Improved Items	All Else	Total	Improved Items	All Else	Total
Flying Hour	96,057	1,238,633	1,334,690	85,359	1,278,528	1,363,886
Per Aircraft	16,953	98,698	115,651	14,736	102,369	117,106
Total	113,010	1,337,331	1,450,341	100,095	1,380,897	1,480,992

Table 21 summarizes the cost per C-5B based on an average of 832 flying hours per year for each PAA. These costs are "Other O&S" cost estimates for either upgrade option.

Table 21. C-5B Cost per PAA Aircraft Flying 832 Hours Annually

	Full Upgrade ($)			Partial Upgrade ($)		
Cost	Improvements	All Else	Total	Improvements	All Else	Total
Flying Hour	106,216	2,446,545	2,552,761	88,359	2,531,317	2,619,676
Per Aircraft	2,439	115,936	118,375	1,886	118,408	120,294
Total	108,655	2,562,481	2,671,136	90,245	2,649,725	2,739,970

Maintenance Creep. For the baseline cost and those items that will not be improved under the various upgrade alternatives, we allow costs to increase by 2 percent per year from FY 2005 through FY 2040. For those items that have been improved, we do not begin the 2 percent growth until the eleventh year following their improvement.

Propulsion. Here we summarize how we estimate the powerplant O&S costs, both for the baseline TF39 engine and for a new 60,000-pound thrust engine.

Baseline C-5 Propulsion System (TF39 Engine). The baseline C-5 engine O&S costs were estimated using current data on the TF39. The TF39 baseline estimate assumes that the

- HT-90 upgrade has been completed
- Improved overhaul maintenance concept that minimizes O&S costs at the aircraft level continues to be implemented
- Increased use of simulator training program that reduces the number of touch and go landing during aircrew training is implemented by the Air Force
- Overhaul of the thrust reverser continues as standard policy.

Detailed discussion of the costing methodology and input data required to estimate the baseline C-5 engine O&S costs is given in Appendix B. Table 22 provides a summary of the input data required for estimating O&S costs for this engine.

Table 22. Input Data for Baseline C-5 Engine O&S Cost Estimates

Input Data	Full Fleet
Engine Flying Hours per Year (Installed)	523.5
Engine Flying Hours before Removal	2,000
% Overhaul / % Other Repair given Removal	85% / 15%
Total Cost per Overhaul & Other Repair	$745 / EFH
On Wing Maintenance Cost per Engine Flying Hour	10% of Overhaul Costs $69.50 / EFH
Thrust Reverser (TR) Overhaul Costs	$20 / EFH
Life-Limited Component Replacement Costs (average based on part by part estimate over 36 years)	$47 / EFH
Fuel cost per A/C Flying Hour	$3,057

Using the data in Table 22, the total engine O&S cost per engine flying hour (EFH) for the baseline C-5 including fuel is estimated to be approximately $1,646. This is for an average C-5 aircraft. For dividing the fleet into C-5A and C-5B, we estimate the number of engine cycles that each fleet generates based on their different flying hour programs and training profiles. This way we can estimate a cost per EFH for each. Table 23 provides the details of this calculation.

Table 23. Apportioning Costs to C-5A & C-5B

Category	Fleet	C-5A	C-5B
Flying Hours	66000	28938	37062
EFH	264000	115754	148246
EFH/Cyc	1.58	1.44	1.70
Cycles	167619	80371	87248
Total Cost	$434,544,000	$208,358,277	226,185,723
Cost/EFH	$ 1,646	$ 1,800	$ 1,526

With these costs per flying hour, we estimate the costs for each of the alternatives once we know how many baseline C-5s are in the inventory by year for each of the alternatives that we are evaluating. In Table 24, we provide the inventory data for each alternative that we used to perform our calculations.

Table 24. Inventory of Baseline C-5s by Calendar Year for Fleet Alternatives

	Number Baseline C-5s in Inventory (No. C-5A / No. C-5B)									
	Year									
Alt	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013-2040
1, 2 & 3	76/50	76/50	76/50	76/50	76/50	76/50	76/50	76/50	76/50	76/50
4 & 5	76/44	76/32	76/14	76/0	76/0	76/0	76/0	76/0	76/0	76/0
6, 7 & 8	76/44	65/32	50/14	35/0	20/0	5/0	0/0	0/0	0/0	0/0
9	76/50	65/50	50/50	35/50	20/50	5/50	0/40	0/25	0/10	0/0

With these inventories, the cost per EFH, and the number of EFHs per year for each type of aircraft, we estimate the baseline C-5 engine O&S costs. There are several small adjustments to this basic approach. First, we adjust our estimates with a cost savings for maintenance when aircraft are being retired or upgraded. This savings accounts for the fact that the engines being removed from the aircraft leaving the fleet have some useful life left, thereby reducing the overhaul requirements for the year that they become available. Also, in Alternative 3, the baselines C-5Bs are changed to guard/reserve status as the upgraded C-5As enter the fleet. This results in additional cost savings for the C-5B fleets due to reduced flying hours. Table 25 provides the resulting baseline C-5 engine O&S cost (FY 2000) estimates for each of the alternatives.

Table 25. Engine O&S Cost Estimates (FY 2000 dollars) for Baseline C-5s by Calendar Year for Fleet Alternatives

Year	1, 2, & 3	4 & 5	6 & 7	8	9
2004	$ 433	$ 372	$ 342	$ 372	$ 433
2005	$ 433	$ 311	$ 269	$ 281	$ 371
2006	$ 433	$ 255	$ 238	$ 185	$ 286
2007	$ 433	$ 207	$ 207	$ 95	$ 213
2008	$ 433	$ 207	$ 175	$ 54	$ 186
2009	$ 433	$ 207	$ 100	$ 14	$ 159
2010	$ 433	$ 207	$ 29	$ -	$ 131
2011	$ 433	$ 207	$ -	$ -	$ 70
2012	$ 433	$ 207	$ -	$ -	$ 16
2013	$ 433	$ 207	$ -	$ -	$ -
2014	$ 433	$ 207	$ -	$ -	$ -
2015	$ 433	$ 207	$ -	$ -	$ -
2016	$ 433	$ 207	$ -	$ -	$ -
2017	$ 433	$ 207	$ -	$ -	$ -
2018	$ 433	$ 207	$ -	$ -	$ -
2019	$ 433	$ 207	$ -	$ -	$ -
2020	$ 433	$ 207	$ -	$ -	$ -
2021	$ 433	$ 207	$ -	$ -	$ -
2022	$ 433	$ 207	$ -	$ -	$ -
2023	$ 433	$ 207	$ -	$ -	$ -
2024	$ 433	$ 207	$ -	$ -	$ -
2025	$ 433	$ 207	$ -	$ -	$ -
2026	$ 433	$ 207	$ -	$ -	$ -
2027	$ 433	$ 207	$ -	$ -	$ -
2028	$ 433	$ 207	$ -	$ -	$ -
2029	$ 433	$ 207	$ -	$ -	$ -
2030	$ 433	$ 207	$ -	$ -	$ -
2031	$ 433	$ 207	$ -	$ -	$ -
2032	$ 433	$ 207	$ -	$ -	$ -
2033	$ 433	$ 207	$ -	$ -	$ -
2034	$ 433	$ 207	$ -	$ -	$ -
2035	$ 433	$ 207	$ -	$ -	$ -
2036	$ 433	$ 207	$ -	$ -	$ -
2037	$ 433	$ 207	$ -	$ -	$ -
2038	$ 433	$ 207	$ -	$ -	$ -
2039	$ 433	$ 207	$ -	$ -	$ -
2040	$ 433	$ 207	$ -	$ -	$ -
Total	$16,033	$7,961	$1,362	$1,001	$1,864

New Propulsion System. The fully upgrade C-5 engine O&S costs were estimated using the 60,000 pound class aggregate engine defined in Appendix B, Volume II. The actual data before aggregation corresponds to the PW 4000, the CF6, and the RB211-524. To avoid discussing any particular engine, we aggregate all three into a notional high-thrust engine. We obtained the data used for these cost estimates by adjusting data from commercial applications to account for the differences between commercial and C-5 military engine usage. The detailed discussion of the costing methodology and input data required to estimate the fully upgraded C-5 engine O&S costs are given in Appendix B. Table 26 provides a summary of the input data required estimating O&S costs for this engine.

Table 26. Input Data for Fully Upgraded C-5 Engine O&S Cost Estimates

Input Data	Full Fleet Upgrade	Partial Fleet Upgrade (All Active)
Engine Flying Hours per Year (Including Spares)	523.5	741
Engine Flying Hours Per Engine Degradation Cycle	1.575	1.575
Engine Degradation Cycles before Overhaul	5200	5200
Cost Per Overhaul	$1,683,333	$1,683,333
On Wing Maintenance Cost per Engine Flying Hour	$12 / EFH	$12 / EFH
FOD/Maintenance Induced Failure Costs	$5 / EFH	$5 / EFH
Thrust Reverser (TR) Overhaul Costs (Inboard Engines Only)	$100,000 per 10,000 EFH	$100,000 per 10,000 EFH
Fuel cost per C-5 Flying Hour	$3,057	$3,057

Using the data in Table 26, the yearly O&S costs are computed for fully upgraded C-5s. These are in Table 27. Once the costs per year of operation are computed, the total C-5 engine O&S cost for a given fleet alternative by calendar year can be computed by appropriate combination of the yearly costs. An example of how this is performed is given in Table 28. For this example, Lot 1 of 10 active aircraft begins operation in 2004, and Lot 2 of 10 active aircraft begins operation in 2005.

Table 27. Fully Upgraded C-5 Engine O&S Costs by Year of Operation Estimates (Full Fleet Upgrade Flying Hour Rate)

Year of Operation	Cumulative Flying Hours	Cumulative Degradation Cycles	Overhauls Costs (4 engines)	On Wing Maintenance (4 engines)	FOD/Maint. Induced Failure Repair (4 Engines)	T/R Overhaul (2 Engines)	Fuel Costs	Total
1	524	332	$ -	$ 25,128	$ 10,742	$ -	$ 1,600,340	$ 1,636,210
2	1047	665	$ -	$ 25,128	$ 10,742	$ -	$ 1,600,340	$ 1,636,210
3	1571	997	$ -	$ 25,128	$ 10,742	$ -	$ 1,600,340	$ 1,636,210
15	7853	4986	$ -	$ 25,128	$ 10,742	$ -	$ 1,600,340	$ 1,636,210
16	8376	5318	$ 6,733,332	$ 25,128	$ 10,742	$ -	$ 1,600,340	$ 8,369,542
17	8900	5650	$ -	$ 25,128	$ 10,742	$ -	$ 1,600,340	$ 1,636,210
18	9423	5983	$ -	$ 25,128	$ 10,742	$ -	$ 1,600,340	$ 1,636,210
19	9947	6315	$ -	$ 25,128	$ 10,742	$ -	$ 1,600,340	$ 1,636,210
20	10470	6648	$ -	$ 25,128	$ 10,742	$ 200,000	$ 1,600,340	$ 1,836,210
35	18323	11633	$ -	$ 25,128	$ 10,742	$ -	$ 1,600,340	$ 1,636,210
36	18846	11966	$ -	$ 25,128	$ 10,742	$ -	$ 1,600,340	$ 1,636,210
37	19370	12298	$ -	$ 25,128	$ 10,742	$ -	$ 1,600,340	$ 1,636,210

Table 28. Example Fleet Full Upgraded C-5 Engine O&S Cost Estimate by Calendar Year

Year	Lot 1 O&S Cost By Year	Lot 2 O&S Cost By Year	Total O&S Cost by Year
2004	$ 16,362,097	$ -	$ 16,362,097
2005	$ 16,362,097	$ 16,362,097	$ 32,724,194
2006	$ 16,362,097	$ 16,362,097	$ 32,724,194
2018	$ 16,362,097	$ 16,362,097	$ 32,724,194
2019	$ 83,695,417	$ 16,362,097	$ 100,057,514
2020	$ 16,362,097	$ 83,695,417	$ 100,057,514
2021	$ 16,362,097	$ 16,362,097	$ 32,724,194
2022	$ 16,362,097	$ 16,362,097	$ 32,724,194
2023	$ 18,362,097	$ 16,362,097	$ 34,724,194
2038	$ 16,362,097	$ 16,362,097	$ 32,724,194
2039	$ 16,362,097	$ 16,362,097	$ 32,724,194
2040	$ 16,362,097	$ 16,362,097	$ 32,724,194

In order to estimate the total fully upgraded C-5 engine O&S costs for each fleet alternative, we require the number of C-5s that will be upgraded in each calendar year for all of the alternatives. Table 29 lists this data for each alternative that we analyze.

Using the data in Table 29, we computed the estimates for the total fully upgraded C-5 engine O&S costs (FY 2000 $M) for each of these alternatives. The resulting cost estimates are given in Table 30.

Table 29. Number of C-5s Upgraded by Calendar Year for Fleet Alternatives

Year Entering	Number of C-5s Upgraded							
	2004	2005	2006	2007	2008	2009	2010	2011
Alternative								
4, 5 & 8	6	12	18	14				
6 & 7	6	12	18	18	18	18	18	18

Table 30. Fully Upgraded C-5 Engine O&S Cost (FY00$) Estimates by Calendar Year for Fleet Alternatives

Year	4, 5 & 8	6 & 7
2004	$ 14	$ 10
2005	$ 41	$ 29
2006	$ 82	$ 58
2007	$ 114	$ 87
2008	$ 114	$ 116
2009	$ 114	$ 145
2010	$ 114	$ 174
2011	$ 114	$ 203
2012	$ 114	$ 203
2013	$ 114	$ 203
2014	$ 114	$ 203
2015	$ 158	$ 204
2016	$ 201	$ 204
2017	$ 244	$ 204
2018	$ 216	$ 205
2019	$ 118	$ 205
2020	$ 120	$ 250
2021	$ 119	$ 292
2022	$ 116	$ 334
2023	$ 116	$ 334
2024	$ 116	$ 336
2025	$ 116	$ 337
2026	$ 116	$ 338
2027	$ 160	$ 338
2028	$ 202	$ 210
2029	$ 244	$ 210
2030	$ 215	$ 210
2031	$ 116	$ 210
2032	$ 117	$ 206
2033	$ 118	$ 206
2034	$ 120	$ 206
2035	$ 119	$ 206
2036	$ 116	$ 206
2037	$ 116	$ 250
2038	$ 116	$ 292
2039	$ 160	$ 334
2040	$ 245	$ 334
Total	$ 4,968	$ 8,095

Other CORE Elements. Here we address the remaining O&S cost elements presented in Table 31. In this table, the cost elements are identified and comments pertinent to the cost element and/or associated estimate are provided. Tailored estimates were developed for maintenance staffing, aircraft depot maintenance, modification kit procurement and installation, sustaining engineering, and software maintenance.

Table 31. O&S Cost Elements Addressed as CORE Elements

Cost Element	Comments
Unit Mission Personnel	
Aircrew	Used crew ratios directed by HQ/AMC
Maintenance	Estimated staffing based on information from staffing projections from HQ/AMC and ANG and reliability data provided by Lockheed Martin
Other Mission	Used AFI 65-503 staffing data to estimate
Aircraft Depot Maintenance (excludes propulsion)	Estimated based on information from WR-ALC on current PDM costs experience and projections and Lockheed Martin on proposed Letter Check Program
Modification Kit Procurement/Installation	Used CORE model algorithm and adjusted costs higher to sustain objective MCR
Support Investment	
Sustaining Engineering	Adjusted to sustain objective MCR
Software Maintenance Support	Estimated based on AMP program
Indirect Support	
Personnel Support	Used CORE model algorithms to estimate
Installation Support	Used CORE model algorithms to estimate

The methods and sources of data used to estimates these costs and the cost estimates derived using these methods are described in full in Volume II, Appendix A and are summarized here.

The main focus is on the following:

- Engine-related costs (as previously discussed)
- Unit level consumption of upgraded subsystems
- Airframe depot maintenance
- Maintenance staffing
- Letter check maintenance concept
- Sustaining support
  - Modifications

- Sustaining engineering
- Software support

- Manpower reductions
  - Active and reserve associate derived from AMC and IDA projections
  - Reserve and guard adjusted for differing maintenance concepts

The treatment is very detailed and can be best followed in Part 3 of this document. The results are summarized in Table 32 for the C-5B. Similar results were obtained for the C-5A.

Table 32. C-5B Factors and Summary of Annual O&S Costs from CORE Model

Cost Factor	Methodology & Sources	Aircraft Configuration			
		Current	Baseline FY 2005	Partial Upgrade	Full Upgrade
Maintenance Space per Aircraft	AMC and IDA estimates	47.75	47.00	44.63	42.13
Depot Maintenance per PAA	PDM experience versus Letter Check projections	$829,500	$829,500	$543,875	$543,875
Annual Modifications per PAA	Adjusted for aircraft cost and MCR rate	$357,892	$363,904	$408,136	$509,624
Sustaining Engineering per PAA	Adjusted for maintaining MCR	$98,684	$100,805	$128,412	$158,470
Software Maintenance per PAA	Adjusted for software complexity	$59,211	$118,421	$118,421	$118,421
Total CORE O&S Cost per PAA	Summary of Cost Factors from CORE	$5.82M	$5.84M	$5.58M	$5.47M

b. C-17 Operating and Support Costs

This segment reviews the O&S costs for the C-17. In this segment, we first review the O&S costs for the propulsion system, then address the other CORE model costs that have been estimated for the C-17. These costs are combined into a total O&S cost estimate.

Propulsion: F117 Engine. C-17 engine O&S costs were estimated only for additional C-17s purchased beyond the current planned buy of 135 (120 baseline + 15 SOF) aircraft. All of these aircraft will have the latest DO-3 version of the P&W F117 engine. We used data for this engine on existing C-17s and on commercial aircraft with this engine to estimate engine O&S costs. Further discussion of the costing methodology and input data required estimating the C-17 engine O&S costs is given in Appendix B. Table 33 provides a summary of the input data required estimating O&S costs for this engine.

Table 33. Input Data for C-17 Engine O&S Cost Estimates

Input Data	Active/Training A/C	Guard/Reserve A/C
A/C Flying Hours per Year (PAA)	1470	700
A/C Flying Hours per Year (TAI)	1336	636
Engine Flying Hours per Engine Degradation Cycle	1.0	1.0
Engine Degradation Cycles before Overhaul	6180 (1st Run), 0.86180 (2nd, ... Runs)	6180 (1st Run), 0.86180 (2nd, ... Runs)
Cost per Overhaul	$1,200,000	$1,200,000
On Wing Maintenance Cost per Engine Flying Hour	10% of Mature OH Cost $24 / EFH	10% of Mature OH Cost $24 / EFH
Fuel cost per A/C Flying Hour	$2,448	$2,448

Using the data in Table 33, the yearly O&S cost for both an Active and a Guard/Reserve C-17 aircraft are computed. An example of this estimate for an Active C-17 is given in Table 34.

Table 34. C-17 Engine O&S Costs by Year of Operation Estimates

Year of Operation	Cumulative Flying Hours	Cumulative Degradation Cycles	Overhauls Costs (4 engines)	On Wing Maintenance (4 engines)	Fuel Costs	Total
1	1336	1336	$ -	$ 128,291	$ 3,271,418	$3,399,709
2	2673	2673	$ -	$ 128,291	$ 3,271,418	$3,399,709
3	4009	4009	$ -	$ 128,291	$ 3,271,418	$3,399,709
4	5345	5345	$ -	$ 128,291	$ 3,271,418	$3,399,709
5	6682	6682	$ 4,800,000	$ 128,291	$ 3,271,418	$8,199,709
6	8018	8018	$ -	$ 128,291	$ 3,271,418	$3,399,709
34	45436	45436	$ -	$ 128,291	$ 3,271,418	$3,399,709
35	46773	46773	$ -	$ 128,291	$ 3,271,418	$3,399,709
36	48109	48109	$ 4,800,000	$ 128,291	$ 3,271,418	$8,199,709
37	49445	49445	$ -	$ 128,291	$ 3,271,418	$3,399,709

Once the costs per year of operation are computed, the total C-17 engine O&S cost for a given fleet alternative by calendar year can be computed by appropriate combination of the yearly costs. An example of how this is performed is given in Table 35. For this example, Lot 1 of 10 active aircraft begins operation in 2004, and Lot 2 of 10 active aircraft begins operation in 2005.

Table 35. Example Fleet C-17 Engine O&S Cost Estimate by Calendar Year

Year	Lot 1 O&S Cost By Year	Lot 2 O&S Cost By Year	Total O&S Cost by Year
2004	$ 33,997,091	$ -	$ 33,997,091
2005	$ 33,997,091	$ 33,997,091	$ 67,994,182
2006	$ 33,997,091	$ 33,997,091	$ 67,994,182
2007	$ 33,997,091	$ 33,997,091	$ 67,994,182
2008	$ 81,997,091	$ 33,997,091	$ 115,994,182
2009	$ 33,997,091	$ 81,997,091	$ 115,994,182
2037	$ 33,997,091	$ 33,997,091	$ 67,994,182
2038	$ 33,997,091	$ 33,997,091	$ 67,994,182
2039	$ 81,997,091	$ 33,997,091	$ 115,994,182
2040	$ 33,997,091	$ 81,997,091	$ 115,994,182

To estimate the total C-17 engine O&S costs for each fleet alternative, we require the number and type of each C-17 that will be added to the alternative fleets in each calendar year. Table 36 lists this data for each alternative that we analyze.

Table 36. Number/Type of C-17s Added by Calendar Year for Fleet Alternatives

	Number/Type of Aircraft (A-active/training, R-guard/reserve)									
Year Entering	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Alternative										
2 & 4	11R	2A/7R								
3 & 5	11R	15R	15R	4A/1R						
7	3A/8R	15A	15A	5A						
8	2A/9R	15A	15A	15A	15A	4A				
9	2A/9R	15A	15A	15A	15A	15A	15R	15R	15R	1A

Using the data we computed the estimates for the total C-17 engine O&S costs for each of these alternatives. The resulting cost estimates are given in Table 37.

Table 37. C-17 Engine O&S Cost Estimates by Calendar Year for Fleet Alternatives

Year	Alternatives				
	2 & 4	3 & 5	7	8	9
2004	$ -	$ -	$ -	$ -	$ -
2005	$ 18	$ 18	$ 23	$ 21	$ 21
2006	$ 36	$ 42	$ 74	$ 72	$ 72
2007	$ 36	$ 66	$ 125	$ 123	$ 123
2008	$ 36	$ 80	$ 142	$ 174	$ 174
2009	$ 36	$ 80	$ 157	$ 235	$ 235
2010	$ 46	$ 80	$ 214	$ 311	$ 348
2011	$ 36	$ 80	$ 214	$ 311	$ 373
2012	$ 36	$ 99	$ 166	$ 311	$ 397
2013	$ 36	$ 80	$ 157	$ 321	$ 431
2014	$ 98	$ 133	$ 253	$ 373	$ 540
2015	$ 70	$ 152	$ 214	$ 311	$ 425
2016	$ 36	$ 171	$ 181	$ 321	$ 434
2017	$ 46	$ 80	$ 214	$ 383	$ 497
2018	$ 36	$ 80	$ 214	$ 330	$ 502
2019	$ 36	$ 99	$ 166	$ 311	$ 425
2020	$ 36	$ 80	$ 157	$ 321	$ 506
2021	$ 46	$ 80	$ 214	$ 330	$ 569
2022	$ 89	$ 133	$ 253	$ 354	$ 545
2023	$ 70	$ 171	$ 166	$ 311	$ 425
2024	$ 36	$ 152	$ 157	$ 321	$ 434
2025	$ 46	$ 80	$ 214	$ 330	$ 502
2026	$ 36	$ 80	$ 214	$ 311	$ 425
2027	$ 36	$ 99	$ 166	$ 311	$ 425
2028	$ 36	$ 80	$ 157	$ 321	$ 506
2029	$ 46	$ 80	$ 214	$ 330	$ 574
2030	$ 89	$ 133	$ 253	$ 354	$ 540
2031	$ 70	$ 171	$ 181	$ 321	$ 434
2032	$ 46	$ 152	$ 214	$ 383	$ 497
2033	$ 36	$ 80	$ 214	$ 330	$ 502
2034	$ 36	$ 99	$ 166	$ 311	$ 425
2035	$ 36	$ 80	$ 157	$ 321	$ 434
2036	$ 46	$ 80	$ 214	$ 330	$ 569
2037	$ 36	$ 80	$ 214	$ 311	$ 502
2038	$ 89	$ 152	$ 205	$ 354	$ 540
2039	$ 70	$ 152	$ 157	$ 321	$ 434
2040	$ 46	$ 152	$ 214	$ 330	$ 502

Other CORE Elements. This Other CORE Elements segment of the C-17A O&S cost estimate addresses the cost elements presented in Table 38. In this table the cost elements are identified and comments pertinent to the cost element and/or associated estimate are provided. In addition to contractor logistics support, detailed estimates were developed for maintenance staffing, aircraft depot maintenance, modification kit procurement/installation, and software maintenance.

Table 38. O&S Cost Elements Addressed as CORE Elements

Cost Element	Comments
Unit Mission Personnel	
Aircrew	Used crew ratios directed by HQ/AMC
Maintenance	Estimated current staffing based on information from AFI 65-503, HQ/AMC and ANG
Other Mission	Used AFI 65-503 staffing data to estimate
Aircraft Depot Maintenance • Excludes propulsion system	Estimated based scaling C-5 experience for PDM costs
Modification Kit Procurement/Installation	Used CORE model algorithm and adjusted costs higher to sustain objective MCR
• Contractor Logistics Support	Based on Boeing Proposal for Flexible Sustainment using FY 2005 as baseline
Indirect Support	
Personnel Support	Used CORE model algorithms to estimate
Installation Support	Used CORE model algorithms to estimate

The methods and sources of data used to estimate these costs and the cost estimates derived using these methods are reviewed below.

C-17 Unit Mission Personnel Costs. *Active Unit Staffing.* This segment addresses the active unit staffing estimates used in the O&S costs estimates for the various configurations of the C-17. In developing the estimate, we used the following staffing information from AFI 65-503 for a typical Active C-17 squadron with 18 PAA. We present in Table 39 the active aircrew staffing requirements provided by HQ/AMC, which were used without change in our study for all configurations of aircraft.

Table 39. C-17 Active Staffing Requirements for a Typical Active 18 PAA Wing

Program Factors	Number of Personnel Needed
PAA	18
Crew Ratio	3
FH/PAA/Yr	1470
Pilots/Crew	2
Non-Pilot Officer/Crew	0
Enlisted/Crew	1.5
II Manpower Factors	
PPE Officers	122
PPE Enlisted	558
PPE Civilian	76
BOS Officers	0
BOS Enlisted	30
BOS Civilians	10
RPM Officers	0
RPM Enlisted	4
RPM Civilians	5
MED Officers	2
MED Enlisted	7
MED Civilians	2
Unit Staff Officers	4
Unit Staff Enlisted	0
Unit Staff Civilians	6
Security Officers	0
Security Enlisted	22
Other Staff Officers	0
Other Staff Enlisted	0
Other Staff Civilians	0

In Table 40 we portray the current maintenance staffing for a C-17 active squadron as reported in AFI 65-503.

Table 40. C-17 Maintenance Staffing Requirements for a Typical Active 18 PAA Squadron

Staff Category	Number of Maintenance Personnel
Officers	10
Enlisted	477
Civilians	48
Total	534

Active Units Maintenance Staffing Adjustments for Extended Fuel Tank Configuration. In developing the IDA adjustments to the maintenance staffing requirements for the extended fuel tank, we used the information in Table 40 and added 0.1 enlisted maintenance spaces per aircraft. These added maintenance positions would be needed to repair the central fuel tank and to perform the added inspections during the Home Station Check. This resulted in two additional maintenance staff personnel per squadron for a total of 536 maintenance staff positions per squadron as portrayed in Table 41.

Table 41. Assessment of Effects of C-17 Extended Fuel Tank Configuration Maintenance Staffing

Staff Category	Number of Maintenance Personnel
Officers	10
Enlisted	479
Civilians	48
Total	536

The revised unit staffing is provided in Table 42.

Table 42. C-17 Extended Range Fuel Tank Configuration Active Staffing Requirements for a Typical Active 18 PAA Wing

II Manpower Factors	Number of Personnel Needed
PPE Officers	122
PPE Enlisted	560
PPE Civilian	76
BOS Officers	0
BOS Enlisted	30
BOS Civilians	10
RPM Officers	0
RPM Enlisted	4
RPM Civilians	5
MED Officers	2
MED Enlisted	7
MED Civilians	2
Unit Staff Officers	4
Unit Staff Enlisted	
Unit Staff Civilians	6
Security Officers	0
Security Enlisted	22
Other Staff Officers	0
Other Staff Enlisted	0
Other Staff Civilians	0

C-17 Reserve Associate Unit Staffing. This segment addresses the Reserve Associate unit staffing estimates used in the O&S costs estimates for the two configurations of C-17: current and extended range. We used the current staffing information available in AFI 65-503 as the basis for our estimates. We present in Table 43 the total C-17 Primary Program Element (PPE) staffing requirements for a Reserve Associate aircrew and maintenance staffing requirements. The AFI 65-503 aircrew staffing was used without change in our study for both configurations of aircraft. The maintenance staffing was adjusted to reflect the slight increase in manpower necessary for the extended range version of the aircraft. Table 44 includes the current C-17 and the extended range version.

Table 43. Air Force Reserve Associate Staffing Including Specific Staffing Adjustments Implemented in O&S Estimate

Program Factors	Number of Personnel Needed
PAA	54
Crew Ratio	3
FH/PAA/YR	0
Pilots/Crew	2
Non-Pilot Off/Crew	0
Enl/Crew	1.5

C-17 Air National Guard Unit Staffing. In developing the estimate, we used the current staffing information provided by the National Guard Bureau and coordinated with ANG/XPP for our estimates. We present in Table 44 the total PPE staffing requirements for an ANG squadron of eight C-17 aircraft. This aircrew staffing was used without change in our study for all configurations of aircraft. The maintenance staffing was adjusted to reflect a slight increase in spaces per aircraft for the extended range aircraft configuration.

Table 44. C-17 Aircraft Air National Guard Unit Staffing Implemented in O&S Estimate

Factors	Number of Personnel Needed
PAA	8
Crew Ratio	5
FH/PAA/YR	275
Crew	
Pilots	2
Total Pilots	80
Enlisted	1.5
Total Enlisted	60

Table 45 portrays for the weapon system staffing requirements for the current C-17 configuration. The maintenance staffing requirements would increase by 4 spaces per aircraft for the extended range version of the aircraft.

Table 45. Weapon System Staffing Requirements

Weapon System Total	Aircrew officer	Aircrew enlisted	Unit Staff + Security	Maintenance	Total
PPE Civilian Technicians		15	13	184	212
AG Officers	12			8	20
AG Enlisted		12	6	39	57
PPE Drill Officers	68		13	41	122
PPE Drill Enlisted		33	48	447	528
Total	80	60	80	719	939
Maintenance Spaces Per Aircraft				89.875	

C-17 Air Force Reserve Unit Staffing. This segment addresses the Reserve unit staffing estimates used in the O&S costs estimates for the two configurations of C-17 aircraft. Since we did not have a estimate from the AFR on the staffing for an Air Force Reserve C-17 Squadron, we used the current staffing information available for an ANG C-17 squadron adjusted by the differences in types of positions as the basis for our estimates. We present in Table 46 the total PPE staffing requirements for AFR Squadron. This aircrew staffing was used without change in our study for all configurations of aircraft. The maintenance staffing was adjusted to reflect a slight increase in spaces per aircraft for the extended range aircraft configuration. Table 46 summarizes the weapon system staffing requirements for the current C-17 configuration. The maintenance staffing requirements would increase by four spaces per aircraft for the extended range version of the aircraft.

Table 46. C-17 Air Force Reserve Unit Staffing Implemented in O&S Estimate

Program Factors	Number of Personnel Needed
PAA	8
Crew Ratio	5
FH/PAA/YR	700
Pilots/Crew	2
Non-Pilot Officers/Crew	0
Enlisted/Crew	1.5
II Manpower Factors (Staffing Positions)	
PPE Total	939
PPE Drill Officers	47
PPE Drill Enlisted	531
PPE Civilian Technicians	260
PPE Civilians	17
BOS Drill Officers	11
BOS Drill Enlisted	21
BOS Civilian Technicians	10
BOS Civilians	11
RPM Drill Enlisted	5
RPM Civilian Technicians	2
RPM Civilians	6
Unit Staff Drill Officers	13
Unit Staff Drill Enlisted	48
Unit Staff Civilian Technicians	13
Unit Staff Civilians	4
PPE Active officers	48
PPE Active enlisted	36

Aircraft Depot Maintenance. This segment provides our estimates for aircraft depot maintenance costs for the C-17A aircraft reflecting a change in maintenance concept that expands the scope of an aircraft depot maintenance program beyond the currently planned Analytical Condition Inspection Program. This more-comprehensive aircraft depot maintenance program includes expanded inspections as aircraft ages, work to perform structural repairs that address corrosion and unpredictable fatigue problems, and a retrofit program to fix specific structural problems that can be predicted from current C-17 structural test and aircraft use information. Our approach to estimating the aircraft depot maintenance O&S costs is to derive a study state estimate that takes into account the potential for cost growth as the C-17 fleet ages. In the structure O&S cost segment that follows we estimate specific aircraft retrofit actions that will have to be accomplished to keep the structural integrity of the C-17 fleet healthy through 2040. Although a significant amount of the projected retrofit costs would be incurred in aircraft depot maintenance activities, those are over and above the costs projected in this segment. Also, the retrofit costs do not include the repair work needed to expand the structural inspections needed as the aircraft ages and to address corrosion problems. The corrosion problems, which cannot be easily predicted as the fleet ages, and other unpredictable structural repair actions will be needed to keep the fleet healthy. All of the latter costs are addressed in this estimate of aircraft depot maintenance costs.

Currently the C-17 aircraft depot maintenance is based on an Analytical Condition Inspection (ACI) program where a C-17A aircraft is inducted every 10 years. The typical types of work performed during ACI include: ACI annual tasks (ACI annual fix hours, ACI phased tasks, ACI phased fix hours) and other tasks including incoming processing, aircraft painting, flight prep tasks, and delivery tasks.)

The ACI program for the C-17 is now being conducted by the Boeing Company under the Flexible Sustainment Contract. Our estimate is based on the assumption that C-17A will require an expanded level of depot maintenance work with aircraft induction every 10 years. Our estimate was derived by scaling the C-17 recurring flyaway costs and aircraft empty weight to the C-5 recurring flyaway cost and aircraft empty weight, and adjusting the estimate to account for the improved material content in the C-17 versus the C-5A/B. This results in an estimate of an average depot maintenance cost of $2.23 million per aircraft, which occurs every 10 years.

Modification Kit Procurement and Installation. The modification and kit procurement and installation O&S costs address the reliability; maintainability and safety modifications needed to allow a weapon system to perform its original mission over its operating life. Using the same approach we used for the C-5, we arrived at the following sustaining engineering costs per year for the current configuration of $98,686, baseline configuration of $100,805, partial upgrade of $128,412, and full upgrade of $153,470. This provided an increase of greater than 50 percent in sustaining engineering funds when comparing the full upgrade configuration to the experience with current configuration.

Our estimate of the O&S cost for the sustaining engineering provides engineering support that is not covered under the contractor logistics contract but is necessary to ensure a weapon system operates safely and effectively throughout its operating life. The tasks include problem definition for both hardware and software elements of the aircraft and for hardware problem resolution through studies, initial designs, breadboard prototypes, and/or engineering change proposals. In O&S cost estimate for the C-17, two activities cover sustaining engineering functions: the Contractor Logistics Support and the resources that cover the integration and work on the common items used on the aircraft. The cost for the common sustaining engineering effort is $10,470 per PAA and was derived from the Air Force Total Ownership Cost data base for FY 1998 as a basis to estimate these costs.

Post-Deployment Software Support. We have reviewed the information provided by the C-17 System Program Office that defines the size and complexity of the software that the Air Force and Boeing plans for the baseline configuration of the C-17A aircraft. Using this information, we estimated the C-17 post-deployment software support costs $22.8 million per year, which translates into a cost per PAA for cases where no additional C-17s are procured at approximately $218,000.

Contractor Logistics Support (CLS). Our estimate for contractor is based on the Flexible Sustainment program currently providing logistics support to the C-17 program. For our estimate the costs for a selected subset of tasks now covered by Flexible Sustainment have been developed. The estimate for CLS includes the following types of tasks now supported through Boeing's Flexible Sustainment Contract:

- Peculiar C-17 consumables
- Peculiar C-17 reparables
- Includes both repair and condemnation replacement
- Peculiar Sustaining Engineering
- Technical Field Support
- Material Management—configuration management, requirements determination
- Base-level engine test cell support

Boeing provided us with a copy of their Flexible Sustainment Proposal, which covers periods through FY 2007. We used the proposal and compared the proposal with the C-17 System Program Office provided Flexible Sustainment Cost Status Report (CSR.) All of these estimates are derived from elements of the costs reported in the Boeing proposal. The cost per flying hour to perform the work is about $1,922 per flying hour. Details are in Volume II.

3. Residual Value And Disposal Costs

The residual value and disposal costs were included to properly account for any residual life that could exist at the end of FY 2040 for the C-17 and the disposal costs of deactivating a C-5 and removing it from inventory in those options that substitute C-17s for C-5s.

The C-5 was assumed to have no residual value in FY 2040, while the residual value for the C-17 would be based on the remaining life in FY 2040 for each aircraft as measured by flying hours. We chose remaining fatigue life as a measure of the C-17's residual value at the end of the study period.

For C-5 disposal costs, we received estimates from Aerospace Maintenance and Repair Center (AMARC) that indicated that the expected costs and value of sales from the bulk materials and spare parts. The available information from AMARC indicates that the funds received by the Government from sale of bulk materials and the return of selected spare parts would significantly exceed the costs of disposing of the aircraft.

For all the C-5 fleet and those C-17 aircraft that had less than 5 percent of its lifetime remaining, we calculated the value of scrapping—money received for the scrap material less disposal costs. We consulted with the Air Force to obtain estimates of the scrap value of each aircraft. The data provided to us showed that they received a return on cost of 15 to 1 for processing aircraft and selling the scrap material. We estimated total cost for the C-5 for transporting, demilitarizing and removing parts to be $75,000. Thus, for the C-5, we estimated a net scrap value after processing of $1.05 million. For the C-17, the net scrap value was $1.0 million, the major reason for the slight difference was the aircraft size difference.

Table 47 presents the results of the residual plus disposal value for each of the alternatives. The table shows the combined residual plus disposal value in both constant year and discounted millions of FY 2000 dollars. They subtract from the total life cycle costs of the alternatives.

Table 47. Residual and Disposal Value for Each Alternative at FY 2040

Alternative	Residual and Disposal Value ($M FY00) Constant Year Dollars	Discounted Dollars
1	132.30	41.57
2	152.30	47.85
3	340.43	106.96
4	152.30	47.85
5	340.43	106.96
6	132.30	41.57
7	340.43	106.96
8	957.04	413.98
9	2,380.07	881.84

G. LIFE CYCLE COSTS

This section presents the life cycle cost results for each of the alternatives. We first present the overall results in Table 48 and then present two more tables (Tables 49 and 50) with more detailed breakdowns. Table 48 should provide enough detail for the reader to summarize the results for other combinations that may be of interest and which have not been shown.

Table 48. Summary of LCC Results by Alternative (all results in billions of dollars)

Alternative	Definition	Constant Dollars ($FY 00)	Discounted Dollars ($FY 00)	Then-Year Dollars
1	Baseline	60.56	32.92	98.57
2	ALT 1 + 20 C-17	72.47	40.83	115.55
3	ALT 1 + 45 C-17	87.31	50.40	137.00
4	Baseline C-5A, Full Upgrade C-5B + 20 C-17	70.27	40.43	110.68
5	ALT 4 + 45 C-17	85.11	50.00	132.13
6	Full Upgrade- All C-5	56.78	32.56	89.50
7	ALT 6 + 45 C-17	83.53	50.04	127.92
8	Full Upgrade-C-5B, Replace C-5A with 75 C-17	80.25	49.02	120.96
9	Replace all C-5 with 132 C-17	88.38	55.40	129.39

Table 49. Summary of LCC Results by Major Cost Categories (all results in billions of dollars)

Alternative	EMD	Procurement	O&S	Residual	Total
Constant Dollars					
1	$ -	$ -	$ 60.69	$ (0.13)	$ 60.56
2	$ -	$ 4.58	$ 68.04	$ (0.15)	$ 72.47
3	$ -	$ 10.27	$ 77.39	$ (0.34)	$ 87.31
4	$ 0.55	$ 6.46	$ 63.41	$ (0.15)	$ 70.27
5	$ 0.55	$ 12.15	$ 72.75	$ (0.34)	$ 85.11
6	$ 0.78	$ 4.93	$ 51.19	$ (0.13)	$ 56.78
7	$ 0.78	$ 15.20	$ 67.89	$ (0.34)	$ 83.53
8	$ 0.55	$ 18.25	$ 62.41	$ (0.96)	$ 80.25
9	$ -	$ 28.14	$ 62.62	$ (2.38)	$ 88.38
Discounted Dollars					
1	$ -	$ -	$ 32.96	$ (0.04)	$ 32.92
2	$ -	$ 3.99	$ 36.89	$ (0.05)	$ 40.83
3	$ -	$ 8.73	$ 41.77	$ (0.11)	$ 50.40
4	$ 0.52	$ 5.60	$ 34.35	$ (0.05)	$ 40.43
5	$ 0.52	$ 10.35	$ 39.23	$ (0.11)	$ 50.00
6	$ 0.74	$ 3.99	$ 27.86	$ (0.04)	$ 32.56
7	$ 0.74	$ 12.73	$ 36.67	$ (0.11)	$ 50.04
8	$ 0.52	$ 15.17	$ 33.74	$ (0.41)	$ 49.02
9	$ -	$ 22.14	$ 34.14	$ (0.88)	$ 55.40
Then Year Dollars					
1	$ -	$ -	$ 98.87	$ (0.30)	$ 98.57
2	$ -	$ 4.96	$ 110.94	$ (0.35)	$ 115.55
3	$ -	$ 11.31	$ 126.47	$ (0.77)	$ 137.00
4	$ 0.56	$ 7.01	$ 103.45	$ (0.35)	$ 110.68
5	$ 0.56	$ 13.36	$ 118.98	$ (0.77)	$ 132.13
6	$ 0.80	$ 5.64	$ 83.35	$ (0.30)	$ 89.50
7	$ 0.80	$ 16.95	$ 110.95	$ (0.77)	$ 127.92
8	$ 0.56	$ 20.46	$ 101.85	$ (1.92)	$ 120.96
9	$ -	$ 32.89	$ 101.59	$ (5.10)	$ 129.39

Table 50. Summary of LCC Results at the Aircraft Configuration Level (Constant Year $FY00, Billions)

Alternative	1	2	3	4	5	6	7	8	9
C 5A									
ACQUISITION (none)									
O&S									
Engine	$ 7.69	$ 7.69	$ 7.69	$ 7.64	$ 7.64	$ 0.64	$ 0.64	$ 0.68	$ 0.59
Other Than Engine	$ 21.45	$ 21.45	$ 21.45	$ 21.45	$ 21.45	$ 1.65	$ 1.65	$ 1.42	$ 1.42
Structural Retrofit	$ 0.33	$ 0.33	$ 0.33	$ 0.33	$ 0.33	$ 0.22	$ 0.22	$ 0.03	$ 0.02
Residual and Disposal	$ (0.08)	$ (0.08)	$ (0.08)	$ (0.08)	$ (0.08)	$ -	$ -	$ (0.22)	$ (0.22)
C 5A Upgrade									
ACQUISITION									
EMD	$ -	$ -	$ -	$ -	$ -	$ 0.48	$ 0.48	$ -	$ -
Engine	$ -	$ -	$ -	$ -	$ -	$ 2.58	$ 2.58	$ -	$ -
Other Than Engine	$ -	$ -	$ -	$ -	$ -	$ 0.47	$ 0.47	$ -	$ -
O&S									
Engine	$ -	$ -	$ -	$ -	$ -	$ 3.89	$ 3.89	$ -	$ -
Other Than Engine	$ -	$ -	$ -	$ -	$ -	$ 18.45	$ 18.45	$ -	$ -
Structural Retrofit	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Residual and Disposal	$ -	$ -	$ -	$ -	$ -	$ (0.08)	$ (0.08)	$ -	$ -
C 5B									
ACQUISITION (none)									
O&S									
Engine	$ 8.35	$ 8.35	$ 8.35	$ 0.32	$ 0.32	$ 0.72	$ 0.72	$ 0.32	$ 1.28
Other Than Engine	$ 22.62	$ 22.62	$ 22.62	$ 0.93	$ 0.93	$ 2.07	$ 2.07	$ 0.93	$ 4.12
Structural Retrofit	$ 0.26	$ 0.26	$ 0.26	$ 0.19	$ 0.19	$ 0.19	$ 0.19	$ 0.19	$ 0.01
Residual and Disposal	$ (0.05)	$ (0.05)	$ (0.05)	$ -	$ -	$ -	$ -	$ -	$ (0.05)
C-5B Upgrade									
ACQUISITION									
EMD	$ -	$ -	$ -	$ 0.55	$ 0.55	$ 0.30	$ 0.30	$ 0.55	$ -
Engine	$ -	$ -	$ -	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ -
Other Than Engine	$ -	$ -	$ -	$ 0.18	$ 0.18	$ 0.18	$ 0.18	$ 0.18	$ -
O&S									
Engine	$ -	$ -	$ -	$ 4.97	$ 4.97	$ 4.21	$ 4.21	$ 4.97	$ -
Other Than Engine	$ -	$ -	$ -	$ 20.23	$ 20.23	$ 19.16	$ 19.16	$ 20.23	$ -
Structural Retrofit	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Residual and Disposal	$ -	$ -	$ -	$ (0.05)	$ (0.05)	$ (0.05)	$ 0.05)	$ (0.05)	$ -
C-17									
ACQUISITION									
EMD	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Engine	$ -	$ 0.39	$ 0.88	$ 0.39	$ 0.88	$ -	$ 0.88	$ 1.46	$ 2.57
Other Than Engine	$ -	$ 4.19	$ 9.39	$ 4.19	$ 9.39	$ -	$ 9.39	$ 14.91	$ 25.56
O&S									
Engine	$ -	$ 1.54	$ 3.44	$ 1.54	$ 3.44	$ -	$ 3.44	$ 10.73	$ 14.97
Other Than Engine	$ -	$ 5.78	$ 13.16	$ 5.78	$ 13.16	$ -	$ 13.16	$ 22.76	$ 39.95
Structural Retrofit	$ -	$ 0.04	$ 0.09	$ 0.04	$ 0.09	$ -	$ 0.09	$ 0.15	$ 0.27
Residual and Disposal	$ -	$ (0.02)	$ (0.21)	$ (0.02)	$ (0.21)	$ -	$ (0.21)	$ (0.68)	$ (2.10)
FY00 Total Cost	**$ 60.56**	**$ 72.47**	**$ 87.31**	**$ 70.27**	**$ 85.11**	**$ 56.78**	**$ 83.53**	**$ 80.25**	**$ 88.38**

Figure 13 shows a graph of the results for constant year dollars. Figures 14 and 15 show the results graphically for discounted and then-year dollars respectively.

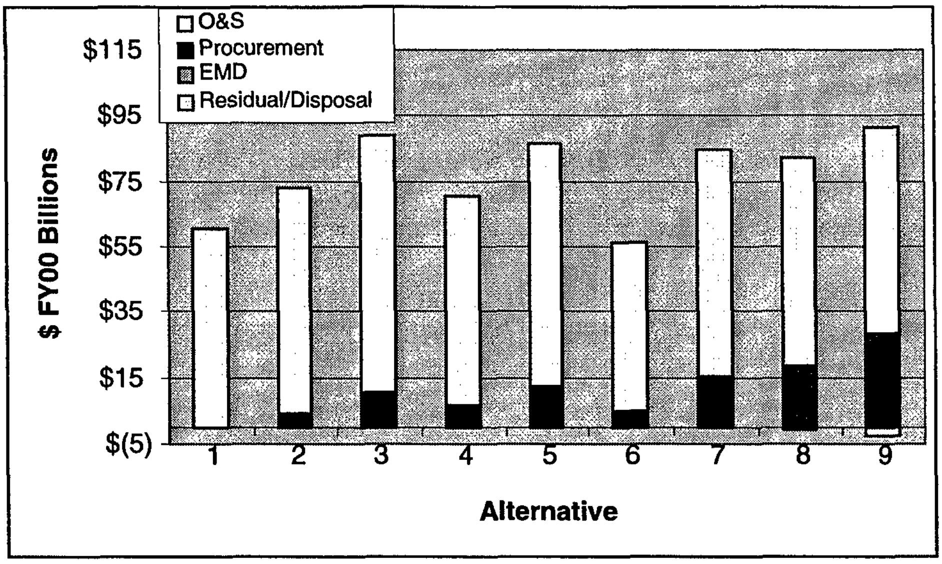

Figure 13. Life Cycle Cost Results by Alternative and Major Cost Category—Constant Year Dollars

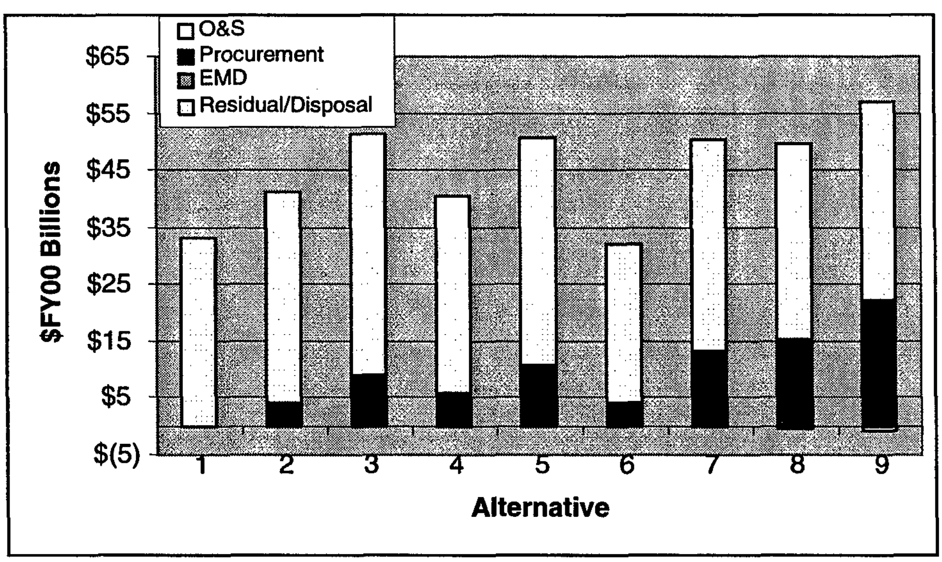

Figure 14. Life Cycle Cost Results by Alternative and Major Cost Category—Discounted Dollars

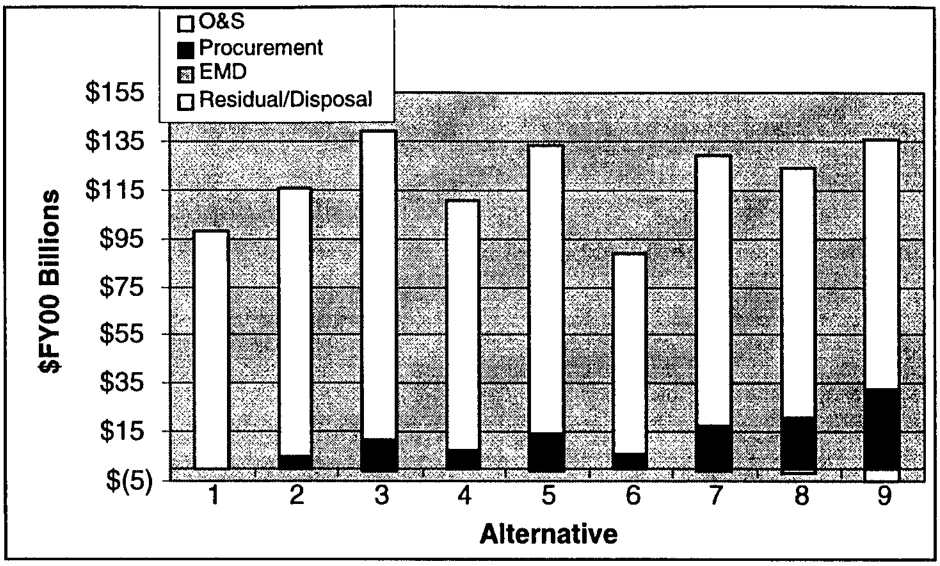

Figure 15. Life Cycle Cost Results by Alternative and Major Cost Category—Then-Year Dollars

Table 51 displays the results in order of increasing LCC. Note that the ordering is the same for constant dollars and discounted dollars and would be the same for then-year dollars except for Alternative 9, which is less costly in then-year dollars than Alternatives 5 and 3.

Table 51. Summary of LCC Results by Alternative—Ordered by Life Cycle Cost (All results in billions of dollars)

Alternative	Definition	Constant Dollars ($FY 2000)	Discounted Dollars ($ FY 2000)	Then-Year Dollars
6	Full Upgrade All C-5	$ 56.78	$ 32.56	$ 89.50
1	Baseline C-5	$ 60.56	$ 32.92	$ 98.57
4	Baseline C-5A,, Full Upgrade C-5B+20 C-17	$ 70.27	$ 40.43	$110.68
2	ALT 1 + 20 C-17	$ 72.47	$ 40.83	$115.55
8	Full Upgrade- All C-5B, Replace C-5A with 75 C-17	$ 80.25	$ 49.02	$120.96
7	ALT 6 + 45 C-17	$ 83.53	$ 50.04	$127.92
5	ALT 4 but + 45 C-17	$ 85.11	$ 50.00	$132.13
3	ALT 1 + 45 C-17	$ 87.31	$ 50.40	$137.00
9	Replace all C-5 with 132 C-17	$ 88.38	$ 55.40	$129.39

From the data displayed in Table 51, we see that Alternative 6, full upgrade of both the C-5A and C-5B has the lowest life cycle cost for all dollar categories. The next lowest cost alternative is Alternative 1, Baseline C-5. It is $3.8 billion more expensive in constant dollars and has a net present value that is about $0.36 billion greater than that of Alternative 6.

Using Net Present Value (discounted), the OMB recommended cost measure for choosing between alternatives, one can group the results as shown in Table 52.

Table 52. Grouping of Alternatives by Net Present Value of LCC

Group	Alternatives	Characteristic	LCC NPV Range ($ Billions)
Low Cost	1 and 6	C-5 Only	$32 - $33
Moderately Low Cost	2 and 4	20 Additional C-17	$40 - $41
Moderately High Cost	3, 5, 7 and 8	45 to 75 Additional C-17	$49 - $51
High Cost	9	All C-17 Airlift Fleet	$55

It should be clear that adding C-17s without replacing any C-5s or changing the flying hour profile of the fleets adds to cost and that is verified by these results. There are two cases where C-17s replace C-5 aircraft. For alternative 8, 75 C-17s replace the 76 C-5A aircraft fleet. However, the LCC of that alternative is only the fifth lowest out of the 9. The other alternative involving C-5 replacement is Alternative 9, whereby all 126 C-5s are replaced by 132 C-7s. This alternative is the most costly of the nine considered.

A natural expectation in considering the C-17 as a viable replacement of C-5 aircraft is that the much higher acquisition cost of the former will be offset by the reduced O&S costs of the C-17 over the 37 years of operation considered in the LCC analysis. Unfortunately, that is not the case. The C-17 does in fact have a lower operating cost but that is offset by a higher flying rate. Table 53 summarizes the comparisons for the "pure fleet" cases—Alternatives 6 and 9 using constant dollars. We see that the O&S cost per flying hour of the C-5 upgraded aircraft is on the order of $21,000, about $7,700 per hour greater than that of the C-17 aircraft. However, to maintain the required crew ratio for the C-17 fleet as well as to meet airlift requirements, the C-17s will fly nearly twice as much per year as does the C-5. As seen in the last column, the lower cost per flying hour of the C-17 does not compensate for the increased flying rate—the fleet O&S cost per year is higher for the C-17. Values in the table exclude mixed fleets in the early years and thus represent steady-state values.

Table 53. Steady-State O&S Cost Comparison—Alternatives 6 and 9 in Constant Dollars ($FY00)

Alternative	O&S Cost per Flying Hour	Flying Hours per Year	Annual Fleet O&S Cost ($B/year)
Alt 6 C-5	$ 21,105	65,928	$ 1.39
Alt 9 C-17	$ 11,983	143,850	$ 1.72

Figure 16 displays the life cycle cost for each of the two alternatives over the 40-year life cycle period considered. The large acquisition cost difference between the C-5 and C-17 in the early years is clearly seen. Also clearly shown in the graph is the higher operating and support cost for the C-17 per year of operation. The sharp drop in cost for Alternative 9 in 2040 is due to the large residual value of the C-17 aircraft fleet in that year. An acquisition differential of about $180 million per aircraft (the cost to buy a C-17 versus that of fully upgrading a C-5) and a relatively high flying rate makes Alternative 9 a very high cost option, despite the residual value benefit.

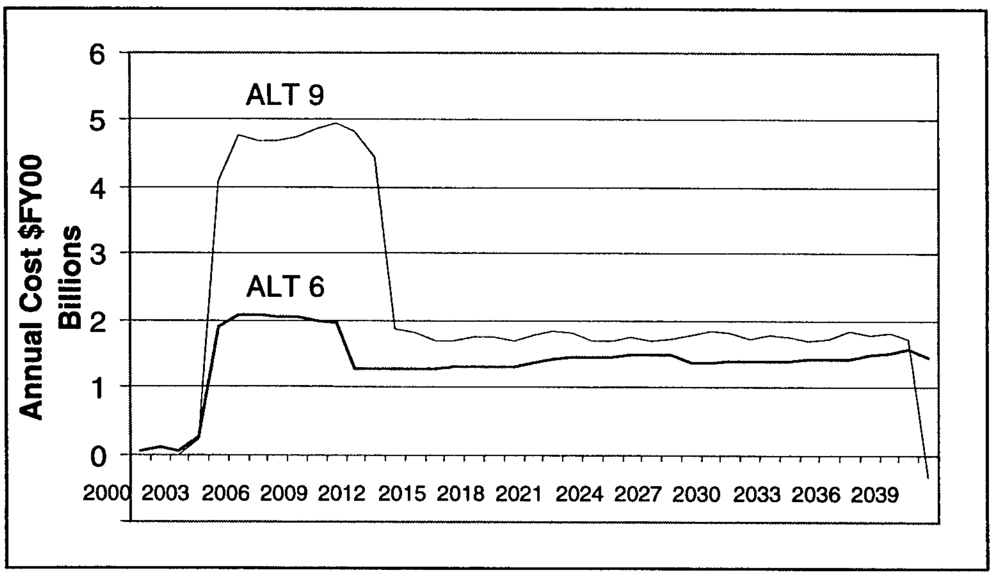

Figure 16. Cost over Time, Alternatives 6 and 9 (Constant FY00 $)

H. COST SENSITIVITY ANALYSES

In this section we explore how sensitive the analyses presented are to different key assumptions. The particular assumptions that are varied are summarized in Table 54. In general these assumptions are ones that may be contentious.

Table 54. Excursions

Variable Whose Sensitivity Is Examined	Basic Assumption	Excursion
C-17 Acquisition Cost	Extrapolations from past acquisition cost plus USAF cost projections for remaining C-17s to be built	Boeing proposal, which is lower than IDA projections
Thrust Needed by C-5 Engine	Commercial 60,000-lb thrust engine derated to 50,000-lb thrust	Commercial 43,000-lb thrust engine, comparable to current TF39 thrust, but more reliable
C-5 & C-17 Flying Hours	Current values	Revised AMC values
Cost of C-5 Modernization Program	Estimates based on IDA assessment of Lockheed Proposal	Revised Higher Cost Estimates from C-5 RERP
Extent of C-5 Upgrade	No partial upgrades to the C-5 were considered by AMC as AoA candidates	A partial upgrade without engine replacement

1. Lower Cost C-17

In March 1999, the Boeing Company submitted a proposal to the Air Force to supply an additional 60 aircraft at an average recurring flyaway price lower than that obtained from extrapolation of past cost experience and USAF budget projections for completing the 120 aircraft buy. These extrapolated values were used in the cost analyses shown earlier in this document.

Others may disagree. They may argue that Boeing has made a proposal that should be the basis for future decisions. So the issue is to what extent are the conclusions to be altered if, in fact, C-17s could be bought at prices reflected by the Boeing proposal (and no additional O&S costs are incurred). As an excursion, we have examined how the fleet LCC would change if the Boeing proposal were used as the basis for estimating C-17 acquisition costs for aircraft beyond 120. The details are found in the proprietary Volume II, Appendix A.

The costs of alternatives with additional C-17s are reduced, but the overall conclusions reached earlier do not change except for the most costly alternatives. Alternative 6 still is the least costly. This is shown in Table 55, where the consequences of the IDA assessment and the Boeing proposal are compared for all nine alternatives. The same information is summarized in graphical form in Figure 17.

Table 55. Comparison of Life Cycle Cost Using IDA and Boeing Prices for Additional C-17s

Alternative	Qty. C-17	Life Cycle Cost (FY2000 $M)			Life Cycle Cost Order (1 =Lowest LCC)	
		Using IDA Projected C-17 Prices	Using Boeing C-17 Prices	Delta IDA – Boeing	IDA	Boeing
1	0	$ 60,556	$ 60,556	$ -	2	2
2	20	$ 72,469	$ 71,296	$ 1,173	4	4
3	45	$ 87,312	$ 84,250	$ 3,063	8	9
4	20	$ 70,267	$ 69,094	$ 1,173	3	3
5	45	$ 85,110	$ 82,047	$ 3,063	7	8
6	0	$ 56,777	$ 56,777	$ 0	1	1
7	45	$ 83,533	$ 80,470	$ 3,063	6	7
8	75	$ 80,255	$ 75,296	$ 4,959	5	5
9	132	$ 88,377	$ 79,262	$ 9,114	9	6

Alternatives 1 and 6 are unchanged with this excursion, since they do not include additional C-17s beyond those already programmed, the cost for which is not included. Alternative 9, with 132 additional C-17s, undergoes the largest drop in LCC; in fact, in this excursion, it no longer is the most costly alternative. Alternatives 3, 5, and 7, relatively close in cost to Alt 9 in the basic estimates, are now more costly.

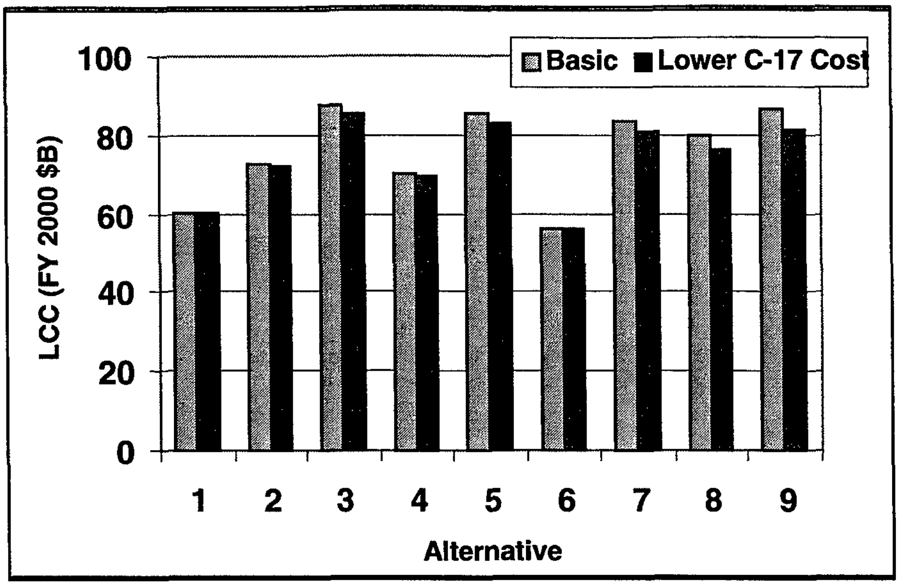

Figure 17. Comparison of LCC Results for Basic and Low Cost C-17 Assumptions

It is our understanding that the USAF may use this excursion as the base case for the AoA. Since the relative cost rankings of the five lowest cost alternatives are not altered in this excursion, decisions made would likely be the same using either the basic or the lower cost C-17 excursion.

2. Low Thrust C-5 Engine

The current plan for re-engining the C-5 is to use an engine in the 60,000-pound thrust class. The current TF-39 engine on the aircraft has a rated thrust of about 43,000 pounds. One of the engine options that was rejected by Lockheed after an earlier analysis is to re-engine with a modern 40,000 pound thrust engine. Several such engines are currently available commercially, for example, the latest version of the Pratt & Whitney F-117, currently used on the C-17, or the Rolls Royce RB211-535. New engines in this same class are currently undergoing testing, so there is a potential competition within this class of engines if a lower thrust (comparable to that currently on the C-5) were acceptable. Because the lower thrust engine brings all the reliability enhancements so often cited as the reason a new engine is needed, but at lower cost and lower weight, it is a reasonable case to consider. Moreover, the argument that a bigger engine is needed for the C-5 is not logically consistent with several of the alternatives in the AOA that involve no upgrades to the C-5 fleet; i.e., there are alternatives that continue using the lower thrust TF39 engine.

An alternative to upgrading the C-5 propulsion system would be to use an engine that provides performance equal to or better than the current TF39 engine for the vast majority of requirements. This engine would provide slightly more than 40,000 pounds of thrust but would have reduced fuel consumption.

The details require use of company-sensitive data and are therefore relegated to the proprietary Volume II, Appendix B. In general we assume that the percent discount rate available to the Government for the 60,000-pound thrust engines would also be attainable for the lower thrust engines in a competitive market. Such an assumption is difficult to validate until an actual competition is held and bids are made. But for the purposes of this AoA it seems a reasonable assumption to make in this excursion. Based on surveying current prices, we concluded that a reasonable list price for a 40k engine was $8.4 million; the estimated 50k engine price is $10 million. Both are discounted to the same percentage amount. The percentage savings of the smaller engine, 16 percent (100 x 0.8/5), was applied to such other factors as EMD, pylons, spares, installation, and management costs.

We also estimated the O&S cost for engine removals based on the commercial experience with such engines, as we did for the higher-thrust class of engines. We obtained the data used for these cost estimates by adjusting data from commercial applications to account for the differences between commercial and C-5 military engine usage. A Detailed discussion of the costing methodology and input data required to estimate the fully upgraded C-5 engine O&S costs is also given in Volume II, Appendix B.

Table 56 summarizes the O&S inputs for the lower thrust engine. The case considered assumes all C-5s are upgraded with a new engine (Alts 6, 7, and 8). Comparable data for alternatives in which some C-5s are upgraded and others are not (Alts 4 and 5) is in Volume II.

Table 56. Input Data for Fully Upgraded C-5 Engine O&S Cost Estimates (40k Engine Excursion)

Input Data	Values
Engine Flying Hours per Year (Including Spares)	523.5
Engine Flying Hours per Engine Degradation Cycle	1.575
Engine Degradation Cycles before Overhaul	5200
Cost per Overhaul	$1,650,000
On Wing Maintenance Cost per Engine Flying Hour	4 Events/1000EFH @ $3000/Event $12 / EFH
FOD/Maintenance Induced Failure Costs	$5 / EFH
TR OH Costs (Inboard Engines Only)	$100,000 @ 10,000 EFH
Fuel Cost per A/C Flying Hour	$2,901

Using the data in Table 66, the yearly O&S costs can be computed for a fully upgraded C-5 in the same fashion we did for the higher thrust engine.

We show results for Alternative 4, upgrade the C-5B fleet only and retain the current C-5A fleet and Alternative 6, upgrade both the C-5A and C-5B fleets. These are compared in Table 67. These two exhaustively cover all cases of comparative interest. Alternatives 1, 2, and 3 do not involve any C-5 upgrades; Alternative 5 is the same as Alternative 4 with respect to the C-5 fleet. Alternative 8 can be "covered" by the Alternative 4 analysis, since it too also involves upgrading only the C-5B fleet, but differs from Alternatives 4 and 5 in that the C-5A fleet is eliminated. Alternative 7 is the same as Alternative 6 with respect to the C-5 fleet and Alternative 9 eliminates the complete C-5 fleet.

Table 57 shows the final results for Alternatives 4 and 6 showing both the engine LCC and the total fleet LCC. The engine LCC values include EMD, pylons, installation, management and fees in addition to the procurement and O&S costs. Note that for Alternative 4, the engine LCC values represent only the C-5B fleet (the O&S costs for the C-5A fleet are about $7.6 billion). However, the total LCC values include all aircraft.

Table 57. LCC Results Comparing the 40k Engine to the 50k Engine Alternatives 6 and 4

Alternative		LCC Costs (FY 2000 $B)	
		C-5 Engine LCC	Total Alt LCC
Alt 4			
Re-Engine C-5B	60k	6.67	70.27
	40k	6.19	69.79
Alt 6			
Re-Engine C-5 A & B	60k	12.38	56.78
	40k	11.38	55.78

It is seen from the table that for Alternative 6, the 40k thrust engine yields a 8.1 percent savings, or slightly over $1 billion, if just engine LCC is considered. From a total LCC perspective, however, this saving amounts to less than 2 percent of the total life cycle cost.

The results for Alternative 4 are in the same direction, but since a smaller portion of the total airlift fleet is being re-engined, the total LCC percentage savings are less than 1 percent.

The C-5 RERP endorses the higher thrust engine. Its Draft ORD explicitly calls for a new engine with capabilities (take-off distance, climb rate) only attainable with the higher thrust engine. The RERP SPO argues that the higher performance is well worth the few percent difference in cost.

3. Flying Hour Excursion

An important parameter in the life cycle costing of the alternatives is the number of flying hours per year. With more flying, O&S costs can be expected to increase because of increased demands on such factors as operational manpower, logistics and maintenance manpower, fuel, spares, and repair materials.[5] Air Mobility Command and

[5] As a potential partial offset, increased flying hours could, in some acquisition and contractor support scenarios, reduce acquisition cost because of the expected increased demand for future contractor support services. This is especially true in a competitive acquisition environment for aircraft engines, where after-market sales are an important profit source for engine manufacturers. This possibility was not explored in the analysis.

the Air National Guard provided data during these analyses that served as the basis for the number of flying hours to be expected annually from each type of aircraft. Because of the significance of flying hours on life cycle cost, AMC has more recently conducted a re-examination of flying hours after the initial analyses were completed and provided IDA with two additional sets of numbers.

In the first flying hour excursion, the ARC-UE, the annual C-5 flying hours are slightly lower than those used in the basic analyses, with the exception of Alts 6 and 7. AMC estimates that the annual C-5 flying hours would be slightly larger in those alternatives. For the C-17, the ARC-UE shows slightly higher flying hours (lower for the Active fleet but higher for the Guard/Reserve), with the exception of Alt 9. In Alt 9, the large number of C-17s (132 extra beyond those programmed) results in lower average C-17 flying hours than assumed in the basic analyses. The details of these assumptions within this excursion are provided in Part 3 (Analyses) as well as in Appendix A of Volume II.

In the second flying hour excursion, Reverse UE, all aircraft flying hours are lower than assumed either in ARC-UE or in the basic analyses. This is particularly true for the C-17 for which the total flying hours per year in the basic analyses are 40 percent higher than in Reverse UE. We do not consider that this assumption would be implemented, so the Reverse UE establishes a lower bound to results expected with lower flying hour experience. We afford higher likelihood to the ARC-UE excursion.

Table 58 compares the average number of flying hours per year used by IDA (Baseline) for all alternatives and the comparable excursion values provided by AMC for the ARC-UE and the Reverse UE cases. Also shown are the total flying hours over the life cycle period, 2004 through 2040.

Table 58. Average Flying Hours Per Year—ARC-UE Case

C-5/C-71 Fleet Hours	Baseline (Applic. Alts)	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Alt 7	Alt 8	Alt 9
C-5 Active and Training	770	676	676	676	695	695	797	797	731	-
C-5 G/R	300	295	295	295	295	295	325	325	-	-
Millions of C-5 Fleet Hours Over 2004-2040	Baseline	2.439	2.439	2.439	2.439	2.439	2.439	2.439	1.411	
	Excursion	2.160	2.160	2.160	2.205	2.205	2.489	2.489	1.312	
C-17 Active and Training	1470	1,430	1,430	1,430	1,414	1,414	1,371	1,371	1,364	1,257
C-17 G/R	700	810	810	810	810	810	810	810	810	810
Millions of C-17 Fleet Hours Over 2004-2040	Baseline		0.484	1.111	0.484	1.111		1.111	2.360	4.920
	Excursion		0.521	1.208	0.520	1.206		1.200	2.372	4.446

Table 59 presents the same information but for the Reverse UE case.

Table 59. Average Flying Hours per Year—Reverse UE Case

C-5/C-17 Fleet Hours	Baseline (All Alts)	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Alt 7	Alt 8	Alt 9
C-5 Active and Training	770	676	676	667	695	671	797	709	741	-
C-5 G/R	300	295	295	295	295	295	325	325	-	-
Millions of C-5 Fleet Hours Over 2004-2040	Baseline	2.439	2.439	2.439	2.439	2.439	2.439	2.439	1.411	
	Excursion	2.160	2.160	2.138	2.205	2.147	2.490	2.281	1.247	
C-17 Active and Training	1470	1,154	1,036	939	1,104	1,104	1,093	1,060	1,050	958
C-17 G/R	700	540	540	540	540	540	540	540	540	540
Million of C-17 Fleet Hours Over 2004-2040	Baseline		0.484	1.111	0.484	1.111		1.111	2.360	4.920
	Excursion		0.366	0.830	0.371	0.853		0.847	1.746	3.343

For the ARC-UE case, the total flying hours for the AMC set of values and those IDA used are fairly close for the C-5, with the Baseline hours greater for all alternatives except for Alt 6 and Alt 7, where the AMC flying rates are a bit higher. For the C-17, the Active fleet yearly rate is lower for AMC, but higher for the Guard/Reserve aircraft. The result is that for all cases except Alt 9, the Baseline C-17 flying hours are lower than the AMC excursion values. Therefore, in general, IDA used higher C-5 flying hours and lower C-17 flying hours, so any flying hour bias in the baseline case would tend to favor the C-17 in the baseline analyses. For Alt 9, where the Baseline flying hours are greater than the AMC excursion flying hours, there is some LCC impact, which is discussed in a later section.

The story is a bit different for the Reverse UE case. Here, the AMC flying rates are lower than for the ARC-UE case and also lower than the flying hour values IDA used. This is especially true for the C-17 where the total flying hours used by IDA are about 40 percent greater than the corresponding AMC excursion values. Note, however, that this case is not considered likely to be implemented and thus, perhaps, best serves as a lower bound to a flying hour excursion.

Instead of doing a detailed life cycle cost analysis we used a much simpler method for determining the impact of flying hour variations by using a cost per flying hour statistic. This statistic was obtainable from the baseline analysis for each alternative. With a flying hour cost estimate in hand, we can then simply multiply it by the expected total flying hours over the life cycle period to quickly derive a new estimate of operating and support cost. We felt that such a method is satisfactory for doing this kind of sensitivity analysis since most of the significant O&S costs are linear with respect to flying hours. Examples of such costs are fuel, depot level reparables (DLRs), and PDM. It is possible that spares costs are not linear and perhaps some CLS costs but, again, we felt the project constraints dictated this quicker method.

Table 60 shows the cost per flying hour statistics derived from the baseline analysis that were used for the flying hour excursions. Two sets of values are shown for the C-17. One set is using the IDA estimates of C-17 acquisition costs based on the past experience for the current fleet, which was adjusted using standard learning curve theory. The second estimate is based on a Boeing proposal in which the acquisition cost is to be reduced under a multiyear procurement contract for additional aircraft. A reduced acquisition cost can be expected to decrease some O&S costs—repair parts, for example, so we see that the flying hour costs are somewhat less for this case.

Table 60. Cost per Flying Hour Statistics

Aircraft	Cost Per Flying Hour
C-5	$ 20,863
C-17- IDA estimate of acquisition cost	$ 11,902
C-17- Boeing MYP Proposed Acquisition Price	$ 11,501

It is clear from Table 60 that whichever of the two C-17 cost per flying hour values are used, this aircraft operates at a much lower cost than the C-5. Can having a flying hour cost about 40 percent less than the C-5 make up for the much higher acquisition cost and lower cargo carrying capacity? The results of the baseline analysis indicate that the answer is no. This flying hour excursion will explore how much of the cost-per-flying-hour benefit the C-17 enjoys can be translated into a LCC benefit by reducing its flying hour requirement (Case Reverse UE).

Table 61 shows the LCC results for the flying hours IDA used, for the AMC ARC-UE and Reverse UE cases using the IDA estimates for the costs of additional C-17 aircraft.

Table 61. LCC Results for Each Alternative Using IDA Estimates for C-17 Acquisition

Case	Estimate	Alternatives 1	2	3	4	5	6	7	8	9
ARC-UE	Baseline Flying Hours	60.56	72.47	87.31	70.27	85.11	56.78	83.53	80.25	88.38
	AMC Excursion Flying Hours	54.74	67.12	82.68	65.83	81.37	57.82	86.64	78.33	82.73
	% LCC Difference	-9.6%	-7.4%	-5.3%	-6.3%	-4.4%	1.8%	2.5%	-2.4%	-6.4%
	LCC Order Baseline	2	4	8	3	7	1	6	5	9
	LCC Order Excursion	1	4	8	3	6	2	9	5	7
Reverse UE	Baseline Flying Hours	60.56	72.47	87.31	70.27	85.11	56.78	83.53	80.25	88.38
	AMC Excursion Flying Hours	54.76	65.28	77.72	64.06	75.97	57.82	77.10	69.53	69.62
	% LCC Difference	-9.6%	-9.9%	-11.0%	-8.8%	-10.7%	1.8%	-7.7%	-13.4%	-21.2%
	LCC Order Baseline	2	4	8	3	7	1	6	5	9
	LCC Order Excursion	1	4	9	3	7	2	8	5	6

The results of these two flying hour excursions are summarized in graphical form in Figure 18. The basic results are shown alongside for reference. For most alternatives, the excursion flying hour assumptions reduce the overall LCC. The exceptions are Alt 6 which undergoes a 2 percent increase in LCC for either of the two excursions and Alt 7 which nearly undergoes a 2.5 percent increase for ARC-UE assumptions. More interesting are the inversions in relative cost that occur with the excursions. In both excursions, Alt 6 is replaced by Alt 1 as the lowest cost alternative. Alt 6 moves to a close second. Note also that Alt 9 is no longer the most costly alternative; it is lower in cost than Alts 3 and 7 for either excursion and lower than Alt 5 for the Reverse UE flying hour excursion. It is also nearly equal in LCC to Alt 8 for the Reverse UE excursion.

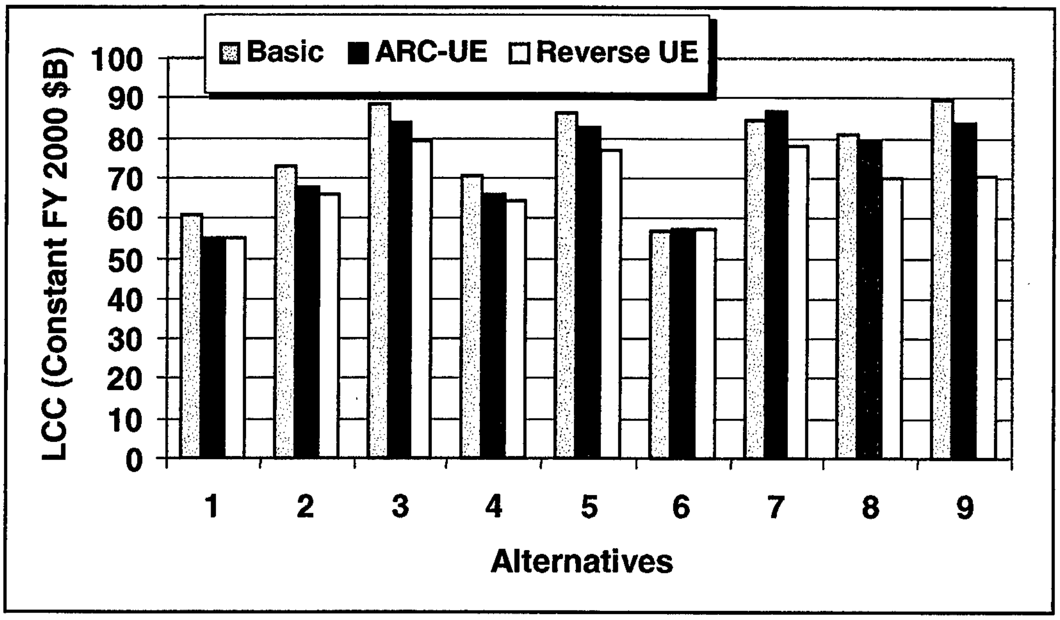

Figure 18. Impact of Flying Hour Excursion on Life Cycle Cost for Alternatives

It is clear from this flying hour analysis that Alternatives 1 and 6 still dominate from a LCC perspective for all three flying hour programs and that any quantity of additional C-17s still extracts a high penalty in life cycle cost. These general conclusions do not change if the Boeing proposed prices for additional C-17s are used.

The LCC ordering for the three sets of LCC results in shown in Table 62

Table 62. Ordering of Alternatives by LCC for Three Flying Hour Programs

LCC Range (Based on Baseline Hours)	Baseline Flying Hours	Excursions	
		ARC-UE	Reverse UE
$60 billion or less	6	1	1
	1	6	6
$61 to $75 billion	4	4	4
	2	2	2
Over $75 billion	8	8	8
	7	5	9
	5	9	5
	3	3	7
	9	7	3

It is seen that the alternatives fall into three groups with respect to life cycle cost, shown by the shading in Table 62.

They are as follows:

- Low Cost ($60 billion or less) – Alternatives 1 and 6
- Moderate Cost ($61 billion to $75 billion) – Alternatives 2 and 4
- High Cost (over $75 billion) – Alternatives 3, 5, 7, 8, and 9.

Note that the low and moderate cost alternatives include no more than 20 C-17s. Within each group the flying hour variations can make some difference in ordering but the groupings are the same for all three flying hour programs considered.

4. Higher C-5 Full Upgrade Acquisition Costs

Our analyses of the cost to fully upgrade the C-5 were derived initially from the 1996 Lockheed Martin study, with adjustments. We have subsequently examined the cost estimates made by the C-5 RERP program office. One major assumption is the concession (or discount) the engine manufacturer would make for such a program. While we feel that the concession we assumed is realistic, a lower concession would increase the C-5 upgrade program. The SPO for the C-5 RERP feels that, among other things, the cost of upgrades should be higher than we assumed. We use the SPO figure here in an excursion.

Figure 19 illustrates the LCC estimates using the SPO figures alongside those of the basic cases considered here. Alts 6 and 7, with the largest number of C-5s being upgraded, show the greatest differences. Yet, despite the differences, the conclusions reached on the basis of the basic assumptions are not changed.

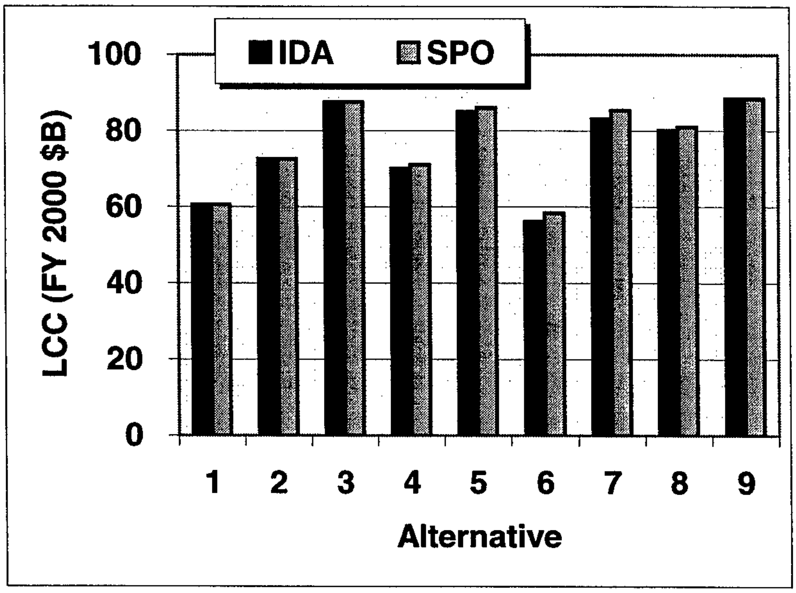

Figure 19. Comparison of Impact of IDA and C-5 RERP Program Office Estimates

5. Partial Upgrade

A reasonable question to ask, when facing the large costs associated with upgrading C-5s or acquiring new C-17s, is what would be the cost (and capability) for a partial upgrade in which all C-5 upgrades *except for re-engining* are implemented. This excursion examines that question.

The AoA conducted by AMC considers only one C-5 upgrade option: Full Upgrade, including new engines of a de-rated 60,000-pound thrust class. We discussed the cost consequences of a lower thrust engine in an earlier excursion. Here we examine the cost and capability consequences of no new C-5 engine at all, but with the other reliability enhancements still included. As noted elsewhere in this paper, we refer to this C-5 configuration as the Partial C-5 Upgrade. Since the new engine acquisition cost accounts for a high percent of the full upgrade cost, a partial upgrade suggests itself as a reasonable alternative to investigate. Is it lower in cost overall than fully upgrading C-5s? The answer turns out to be no. The Full Upgrade is lower in life cycle cost. We show the details below.

We have conducted a cost analysis of two excursions with partial C-5 upgrades. One is the same as Alt 6 except that no re-engining costs are included. Other engine-related costs associated with a new engine were also identified and deleted for this excursion. By AMC estimates, the partial upgrade excursion falls short in capacity (measured in MTM/D) from that required in MRS BURU and presumably required in MRS-05. To attain the 27.1 MTM/D capacity for over- and out-size cargo that MRS BURU required, 10 additional C-17s must be acquired to make up the shortfall for a partial upgrade option. Thus the second partial upgrade excursion we consider is identical to the first as far as C-5 upgrades are concerned but possesses 10 additional C-17s.

Table 63 summarizes the detailed cost assessments we made for these two excursions. Alts 1 and 6 are also shown for comparison. The acquisition costs are further decomposed into EMD costs, costs for acquiring new engines (if any), and other costs. This permits a clear view of the relative contribution of engines to the overall acquisition cost for each alternative. The O&S costs are similarly decomposed into engine O&S, costs for structural retrofits through 2040, and other costs. Again, the engine contribution is made manifest by this decomposition. The cost entries in this table are in constant FY 2000 millions of dollars. From these and the time phasing we also have calculated discounted dollars and then-year dollars, summarized at the end of this table.

A few details may be useful to point out in Table 63. Note that, although Alt 6 has no baseline C-5s, O&S costs are associated with baseline C-5A and B entries. These costs are associated with the C-5 O&S before upgrading, since not all 126 C-5 aircraft are upgraded immediately. O&S costs from 2001 through 2040 are calculated for each aircraft individually. Until it is upgraded, its costs are at the baseline C-5 level. After upgrading and through 2040, the O&S costs are for the upgraded configuration.

Table 63. Cost Details and Comparisons for Partial Upgrade Excursions

Type Of Aircraft And Cost Category	Alternatives			
	Alt 1	Partial Upgrade Excursion	Partial Upgrade Excursion, Add 10 C-17s	Alt 6
Baseline C-5A				
Number of Baseline C-5s	*76*	*0*	*0*	*0*
O&S Cost				
Engine	$ 7,687	$ 812	$ 812	$ 644
Other Than Engine	$ 21,446	$ 1,646	$ 1,646	$ 1,646
Structural Retrofit	$ 28	$ 328	$ 328	$ 222
Residual and Disposal Cost	$ (80)	$ -	$ -	$ -
C-5A Upgrade				
Number of C-5s Upgraded	*0*	*76*	*76*	*76*
Acquisition Cost				
EMD	$ -	$ 27	$ 27	$ 140
Engine	$ -	$ -	$ -	$ 2,582
Other Than Engine	$ -	$ 465	$ 465	$ 474
O&S Cost	$ -	$ -	$ -	$ -
Engine	$ -	$ 6,875	$ 6,875	$ 3,887
Other Than Engine	$ -	$ 18,740	$ 18,740	$ 18,452
Structural Retrofit	$ -	$ -	$ -	$ -
Residual and Disposal Cost	$ -	$ (80)	$ (80)	$ (80)
Baseline C-5B				
Number of Baseline C-5s	*50*	*0*	*0*	*0*
O&S Cost				
Engine	$ 8,345	$ 907	$ 907	$ 718
Other Than Engine	$ 22,622	$ 2,069	$ 2,069	$ 2,069
Structural Retrofit	$ 260	$ 260	$ 260	$ 190
Residual and Disposal Cost	$ (53)	$ -	$ -	$ -
C-5B Upgrade				
Number of C-5s Upgraded	*0*	*50*	*50*	*50*
Acquisition Cost				
EMD	$ -	$ 18	$ 18	$ 92
Engine	$ -	$ -	$ -	$ 1,700
Other Than Engine	$ -	$ 175	$ 175	$ 179
O&S Cost				
Engine	$ -	$ 7,438	$ 7,438	$ 4,208
Other Than Engine	$ -	$ 19,646	$ 19,646	$ 19,160
Structural Retrofit	$ -	$ -	$ -	$ -
Residual and Disposal Cost	$ -	$ (53)	$ (53)	$ (53)

Table 63. (Continued)

Type Of Aircraft And Cost Category	Alternatives			
	Alt 1	Partial Upgrade Excursion	Partial Upgrade Excursion, Add 10 C-17s	Alt 6
C-17				
Additional C-17s Beyond No. Programmed	*0*	*0*	*10*	*0*
Acquisition Cost				
EMD	$ -	$ -	$ -	$ -
Engine	$ -	$ -	$ 195	$ -
Other Than Engine	$ -	$ -	$ 2,076	$ -
O&S Cost				
Engine	$ -	$ -	$ 775	$ -
Other Than Engine	$ -	$ -	$ 2,908	$ -
Structural Retrofit	$ -	$ -	$ 18	$ -
Residual and Disposal Cost	$ -	$ -	$ (10)	$ -
FY 2000 Total Cost	$ 60,556	$ 59,274	$ 65,236	$ 56,777
Discounted Total Cost	$ 32,919	$ 32,482	$ 36,473	$ 32,558
Then Year Total Cost	$ 98,574	$ 96,015	$ 104,477	$ 89,497

Figure 20 shows the LCCs (discounted dollars) for the two partial upgrade excursions, both derived from Alternative 6 (which has a full upgrade to all 126 C-5s). The Baseline Alt 1 and Alt 6 are also shown in Figure 20 for comparison. In addition to the total LCC through 2040, the cost for acquisition, operating and support, and residual/disposal are also shown. This graph provides a more summary view of the data from the table just discussed. The residual/disposal cost is so small that it is nearly impossible to see on this graph. Thus the dominating costs are acquisition and, to an even larger extent, O&S. The first partial upgrade excursion is identical to Alt 6 except that it does not include re-engining, so retains the TF39, the same engine found in the Baseline C-5s. Its acquisition cost, as shown in the figure, is considerably lower than that of Alt 6. The other partial upgrade excursion also retains TF39s for the C-5s but includes 10 additional C-17s beyond those already programmed. Its acquisition cost, even with the 10 C-17s, is also lower than that of Alt 6.

As can be seen in this figure, a partial upgrade (with no additional C-17s) reduces the fleet LCC by over $0.4 billion. This indicates the value of all the upgrades other than the engine replacement. Such upgrades also increase the MTM/D capacity from the Baseline, although they fall short of the goal. On the other hand, the addition of enough

C-17s to attain the goal capacity of 27.1 MTM/D incurs a large cost increase. The LCC for the partial upgrade excursion then rises to $36.5 billion, well above the $32.6 billion LCC for Alt 6.

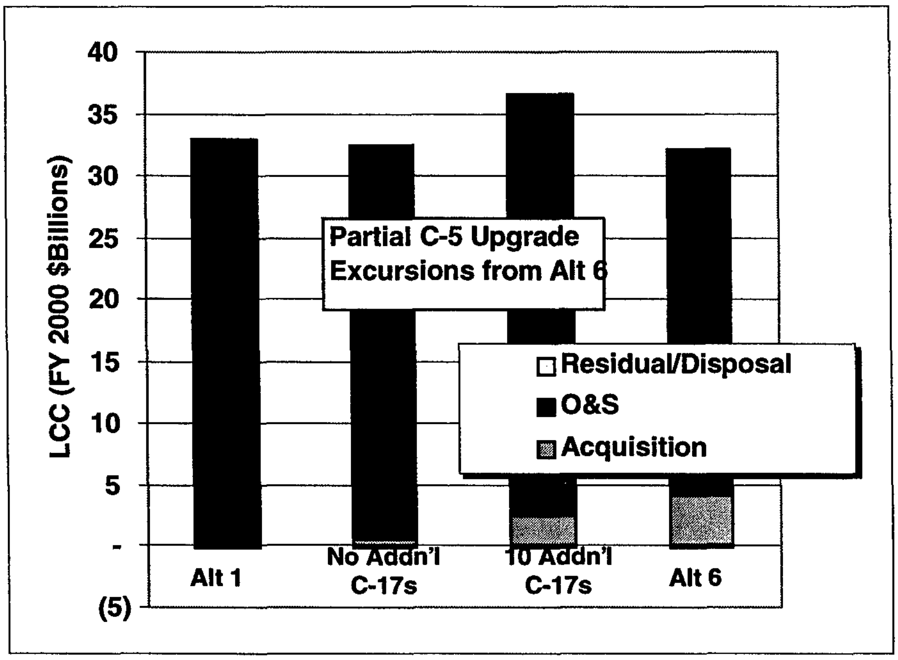

Figure 20. Comparison of Partial Upgrade Excursions with Basic AoA Alternatives, Including Decomposition by Acquisition, O&S, and Residual/Disposal Cost

Our analyses show that, even though the C-5 re-engining is costly, the LCC for a re-engined C-5 fleet is lower than one without re-engining. The less costly re-engined C-5 fleet also has a higher MTM/D capacity than those not re-engined. When comparable capacity is required, the alternative with re-engined C-5s (Alt 6) is considerably less costly than the partial upgrade excursion with non-re-engined C-5s, since additional C-17s must be bought and operated. As noted earlier, the O&S costs for these additional 10 aircraft account for all of the cost increase over Alt 6.

6. Cost Risk Analysis

The previous section on sensitivity analysis addresses the effects of varying a single important factor (e.g., C-17 cost, C-5 EMD cost, partial upgrade, etc.) on life cycle cost. To assess the overall cost risk for each alternative we must vary multiple factors simultaneously, not just one at a time.

The risk analysis approach does not use a single value for the cost of the important factors, but instead associates a specified uncertainty with each factor. This leads in turn to a distribution of life cycle costs for each alternative rather than to the point estimates cited earlier. The uncertainty is captured via a probability distribution of costs for each factor over a reasonable range of costs. A statistical sampling model is then used to calculate the life cycle cost distributions.

We used the Crystal Ball/Excel simulation model to dynamically change selected estimated values in accordance with triangular distributions. We ran the model 5,000 times to minimize sampling fluctuations.

First we discuss what factors were considered for the risk assessment. Then we briefly discuss the distributions and finally show the results.

a. Cost Risk Factors

The AoA involves many dozens of individual estimates, which combine to form the overall life cycle costs of the alternatives. The cost risk factors we selected are based on our experience to be ones that drove overall costs or ones that were contentious. The factors used were:

1) C-5 Cost Factors
   - RERP
     - Engineering and Manufacturing Development
     - Procurement
       - Airframe
       - Engine
   - O&S
     - Failure-related risk costs—GSD/FH and MSD/FH
     - Engine
     - Other non-engine O&S costs—maintenance manpower, sustaining engineering, depot maintenance (aircraft level including letter check and excluding engine), R&M and safety modifications,

2) C-17 Cost Factors
   - Aircraft procurement

- O&S
  - Engine
  - Other non-engine

b. Probability Distributions

For each of the above factors, we assigned a probability distribution representing the uncertainty or risk in our estimate of the cost. In most cases we had a reasonable basis for a low and high estimate but not the form of the distribution. As is often done in such situations, we used a triangular distribution, with the peak at our best estimate.

It is conceivable that some of the cost-risk measures are *correlated.* For example, the O&S costs for the C-5 and C-17 engines may be correlated to the extent that they may depend on identical factors, such as the cost for engine-related materials and labor. Where the correlation was known to be very high—such as O&S costs for a given aircraft for each of the alternatives—with aircraft quantities being the major differences among the alternatives, we used the same cost-risk factor, equivalent to having a correlation of 1.0. For other cases, since we did not have any means of determining the amount of correlation within the scope of this study, we chose to assume that the variables are independent. Since correlated variables increase the variance of the output, this assumption tends to lead to tighter output distributions than may actually be the case.

c. Limits and Distributions Used in the Analysis

The following sections will review how the low and high estimates were obtained for the selected cost-risk factors.

C-5 Acquisition Costs. For this category, we chose two basic cost elements: the EMD associated with the C-5 RERP program and the procurement cost for the C-5 RERP. The basis for the point estimates are documented earlier in this analysis with the EMD based on analogy to the KC-135R program and the procurement costs based on Lockheed Martin information.

Risk estimates for C-5 RERP EMD were developed after examining different contractor proposals for the RERP. For the C-5 RERP procurement risk estimates, we divided the risk assessment into engine related and non-engine related. For the engine cost risk estimates, we varied the concession expected about the number we used in our point (best) estimates, based on historical experience. The non-engine procurement estimates were varied in the same proportion as EMD. Details on all these can be found in the more detailed risk assessment description provided in Appendix A in Volume II. Table 64 shows the low, most likely (our best estimate), and high estimates as ratios of the most likely costs.

Table 64. Cost Risk Factors for C-5 Acquisition Costs

Cost Factor	Low	Most Likely	High
C-5 RERP EMD	0.66	1.00	1.12
C-5 RERP Engine Procurement	0.88	1.00	1.24
C-5 RERP Non-engine Procurement	0.66	1.00	1.12

C-5 O&S Failure-Related Cost Risks. For this category, we selected two basic cost elements to vary: the General Support Division (GSD) costs per flying hour and the Material Support Division (MSD) costs per flying hour. The former includes general bulk supply consumables and the latter special consumables (formerly denoted by SSD) and the depot level reparables (DLR). The data we used for the point estimates were developed from analyses initially conducted by AMC and later reviewed by the Air Force Cost Analysis Agency. We had to modify the data for one or more of the following reasons:

1. Some of the results showed inconsistencies relative to the C-5A and C-5B aircraft so we used an average of A and B data weighted by the expected flying hours per year for each aircraft type. For example, because the C-5A aircraft is older and generally more unreliable than the C-5B, we would expect that on a flying-hour basis, the cost for the former should be higher than the latter. That was not always the case.
2. The GSD and MSD data included costs for engine items that had to be removed from engines and are treated separately.
3. The GSD and MSD data included costs for avionics that also had to be removed since the whole avionics package was to be replaced.
4. We had to segregate the items that the upgrade would affect from those that would remain essentially the same so that improvements only affected the applicable portion of GSD and MSD.

Table 65 shows the low, most likely, and high estimates that were used in the risk analysis: These values for GSD and MSD are for the total aircraft; they are then adjusted for engines and avionics as well segregated for improved and non-improved portions of the aircraft.

Table 65. Cost Risk Factors for C-5 Failure-Related Costs, Expressed in Dollars per Flying Hour

Cost Factor	Low	Most Likely	High
GSD/FH	847	918	1,017
MSD/FH	2,171	2,852	3,159

For the GSD distribution, we used the low and high values of AFI 65-503 data over the years 1996, 1997, and 1998, after adjusting them to the FY00 base year dollars. For the MSD values, we used the low value of the same data but the high value was a bit lower than our expected value. Therefore, we estimated an upper limit by using the ratio of Upper Limit GSD to Expected Value GSD as a multiplying factor to the expected MSD value.

C-5 Other Non-Engine O&S Cost Risks. For this category of risk, we selected five cost elements to vary: maintenance spaces per aircraft, software support cost per PAA, sustaining engineering cost per PAA, aircraft level depot maintenance cost per PAA, and R&M and safety modifications. Table 66 shows the low, most likely, and high estimates used in the study. The data we used for the point estimates were those defined previously in the study. To derive the limits for each of the cost elements we applied various techniques as described in Appendix A in Volume II for each category.

Table 66. Cost Risk Factors for C-5 Other Non-Engine O&S Cost Elements

Cost Factor	Low	Most Likely	High
Maintenance Spaces per Aircraft	40.5	42.36	44.86
Software Support Cost/PAA/Year	$122,728	$125,000	$130,263
Sustaining Engineering/PAA/Year	$127,841	$153,470	$168,817
Level Depot Maintenance Cost/PAA/Year	$459,453	$543,875	$643,871
R&M and Safety Modifications Cost/PAA /Year	$418,872	$462,025	$509,624

When the low and high estimates for the above factors were combined with the remaining cost elements, we found that it was sufficient to apply overall factors of 0.96 and 1.04 to the most likely estimate of O&S cost per PAA to get the distributional parameters for C-5 non-engine O&S cost risks.

C-5 Engine O&S Cost Risks. Five separate cost elements were selected as cost risk factors for the C-5 engine O&S costs: two related to the current engine and three related to the replacement engine. For the current engine, we selected the cost to overhaul the engine and the time to first overhaul as the cost risk factors. Table 67 shows the low, most likely, and high estimates for these factors:

Table 67. Cost Risk Factors for Current TF39 C-5 Engine O&S Costs

Cost Factor	Low	Most Likely	High
C-5 Current Engine Overhaul Cost ($ millions)	1.3	1.6	1.9
C-5 Current Engine Time Between Overhauls (hours)	1,975	2,304	2,633

A best estimate of $1,600,000 was used for the overhaul cost, with a cost range of plus and minus $300,000 (~20 percent). For the time between overhauls, we used existing data and estimates from San Antonio Air Logistics Center (ALC) and several offices at Wright Patterson AFB on the potential of the new overhaul policy for the TF39. These estimates include an adjustment for the expected reduction in the number of touch-and-go's (where an aircraft just barely lands before taking off again) in future training operations.

For the C-5 replacement engine, the cost risk factors selected were the engine overhaul cost, the time to first overhaul and the expected fuel savings expressed as a percentage of current engine fuel costs. Table 68 shows the estimates for the C-5 replacement engine O&S cost factors.

The ranges for the engine overhaul costs and time to first overhaul were based on an examination of different contractor estimates for these factors. The distribution is wider about the replacement engine overhaul rate than for the TF39 because of greater experience with the TF39 on a C-5. The fuel cost range was agreed upon during meetings with the C-5 and Propulsion SPOs at Wright Paterson AFB.

C-17 Acquisition Costs Risks. For this category, we used two basic cost elements: the acquisition costs for the engine and the acquisition costs for the remainder of the aircraft as the cost risk factors.

Table 68. Cost Risk Factors for Replacement C-5 Engine O&S Costs

Cost Factor	Low	Most Likely	High
C-5 Replacement Engine Overhaul Cost ($ millions)	1.1	1.683	2.25
C-5 Replacement Engine Time to First Overhaul (hours)	7,600	8,200	8,700
C-5 Replacement Engine Fuel Cost Benefit (percentage over current TF39)	-2%	+2%	+5%

The C-17 engine procurement risk estimates were developed based on the concessions that we believe possible for the procurement of the F-117 engine. Except for the thrust reverser, this engine is essentially a commercial engine. The high estimate was based on one standard deviation of regressed actual experience. For the "non-engine aircraft procurement" risk estimates for the C-17, we used the Boeing proposal as the low, the IDA estimate for these costs as the most likely, and two standard deviations above the IDA estimate regression as the basis for the high estimate. The procurement risk estimates are based on ratios comparing the low and high estimates against the most likely estimates. Table 69 shows the low, most likely, and high estimates as ratios of the most likely costs.

Table 69. Cost Risk Factor Ratios for C-17Acquisition Costs

Cost Factor	Low	Most Likely	High
C-17 Engine Procurement	0.72	1.00	1.07
C-17 Non-engine Aircraft Procurement	0.80	1.00	1.25

C-17 Non-Engine O&S Cost Risks. For this category of risk, we selected the following cost elements to vary:

- Contractor logistics support cost per flying hour, which includes C-17 peculiar spares (consumables and reparables), sustaining engineering, technical field support, material management, and base-level engine test cell support
- Common item General System Support consumable spares
- Common item depot level reparables
- Aircraft level annual depot maintenance cost per aircraft
- R&M and safety modifications

- Software.

The data we used for the point estimates were as defined previously in this study. Table 70 shows the low, most likely, and high estimate used in the study. To derive the limits for each of the cost elements we applied various techniques described in Appendix A in Volume II.

Table 70. Cost Risk Factors for C-17 Non-Engine O&S Costs, Expressed in FY 2000 Dollars

Cost Factor	Low	Most Likely	High
Contractor Logistics Support/FH	$1,837	$1,922	$2,345
Common Item General Systems Support/FH	$371	$412	$503
Common Item Depot Level Reparables/FH	$485	$539	$658
Aircraft Level Depot Maintenance/PAA/year	$168,395	$222,511	$315,741
R&M and Safety Modifications/PAA/year	$457,274	$477,446	$495,056
Software Cost/PAA/year	$178,824	$223,529	$268,235

When combining these low and high estimates with the most likely estimates for others cost elements, we found that it was sufficient to multiply the most likely estimate of C-17 non-engine O&S cost by 0.9 and 1.06 to get the low and high triangular distribution limits, respectively.

C-17 Engine O&S Cost Risks. For the C-17 engine, the time to first overhaul and the overhaul cost were the selected cost risk factors. Values used are shown in Table 71.

Table 71. Cost Risk Factors for C-17 Engine O&S Costs

Cost Factor	Low	Most Likely	High
C-17 Engine Overhaul Cost ($ millions)	1.0	1.2	1.4
C-17 Engine Time to First Overhaul (number of cycles)	3,500	6,180	8,000

A best estimate of $1,200,000 was used for the overhaul cost. A cost variance of plus and minus $200,000 was used for the high and low values, respectively—about the same 20 percent used for the TF39 on the C-5. For the time to first C-17 engine overhaul, the lower estimate of 3,500 cycles is based on an earlier (DO-1) engine configuration. The high estimate is based on the best commercial data we had for the engine.

d. Results of the Cost Risk Analysis

Results of the Cost Risk Analysis—IDA Prices for the C-17. Table 72 presents the results of our cost risk analysis. Included at the top of the table are the best estimates given earlier for the nine alternatives. Estimates include both constant year and discounted dollars and the ranking based on constant year dollars.

The first set of risk-analysis results shows the rankings for the nine alternatives that result from the Crystal Ball model runs. As to be expected, there is very high correlation between the best estimate ranking and that produced by the risk analysis. Somewhat unexpected was the fact that for the five lowest cost alternatives (Alts 6, 1, 4, 2, and 8 – in that order), there was not a single trial in which the alternative deviated from its comparative ranking. These alternatives have an asterisk (*) next to the Rank Cost Risk column heading. For example, in all of the 5,000 trials, Alt 6 always ranked as the lowest cost alternative. We also see that Alt 9, in which the C-5 fleet is replaced with the C-17 fleet has the largest spread, appearing as low as Rank 6 but still having an average rank of almost 8.7, the highest mean-rank of the set.

The actual constant-year life cycle costs produced by the risk analysis along with the statistics on cost variation are shown in the second set of statistics contained in the table; the same results in terms of present value are shown in the third set. Note how closely the mean and median estimates match the best estimates. For example, for Alt 2, the best estimate was $72.47 billion and the risk analysis produced a mean of $72.40 and a median of $72.38. The closeness of the mean and median across all alternatives indicates symmetry. This is to be expected since the initial range of cost inputs for the triangular distributions were, for the most part, not too asymmetrical and theory tells us that when distributions of most any kind are summed, the resulting distribution tends to be normal.

Crystal Ball also provides graphical summaries of the results, illustrated in Figures 21 and 22. The former shows the life cycle cost distribution in constant year dollars for each alternative and the latter the corresponding graphs using discounted (PV or present value) dollars.

Table 72. Summary of Statistics of Cost-Risk Measures for the Life Cycle Cost Analysis IDA Estimates of C-17 Prices ($ Billions)

Statistic	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Alt 7	Alt 8	Alt 9
Best Estimate $FY00	$60.56	$72.47	$87.31	$70.27	$85.11	$56.78	$83.53	$80.26	$88.38
Best Estimate $PV	$32.92	$40.83	$50.40	$40.43	$50.00	$32.65	$50.12	$49.02	$55.40
Best Estimate Ranking	2	4	8	3	7	1	6	5	9
$FY00 COST RISK MEASURE	**Alt 1 $FY00**	**Alt 2 $FY00**	**Alt 3 $FY00**	**Alt 4 $FY00**	**Alt 5 $FY00**	**Alt 6 $FY00**	**Alt 7 $FY00**	**Alt 8 $FY00**	**Alt 9 $FY00**
Mean	$60.51	$72.40	$87.21	$70.30	$85.12	$57.01	$83.72	$80.42	$88.45
Median	$60.51	$72.38	$87.20	$70.30	$85.10	$57.02	$83.71	$80.35	$88.35
Standard Deviation	$0.99	$1.07	$1.38	$0.88	$1.24	$0.66	$1.17	$1.68	$2.76
Range Minimum	$57.37	$68.92	$82.72	$67.56	$81.06	$54.85	$80.00	$75.52	$80.68
Range Maximum	$63.72	$75.95	$91.78	$73.29	$89.57	$59.11	$87.83	$86.70	$97.91
$PV COST RISK MEASURE	**Alt 1 $PV**	**Alt 2 $PV**	**Alt 3 $PV**	**Alt 4 $PV**	**Alt 5 $PV**	**Alt 6 $PV**	**Alt 7 $PV**	**Alt 8 $PV**	**Alt 9 $PV**
Mean	$32.89	$40.80	$50.38	$40.47	$50.04	$32.79	$50.28	$49.15	$55.49
Median	$32.89	$40.80	$50.35	$40.46	$50.03	$32.78	$50.26	$49.11	$55.44
Standard Deviation	$0.54	$0.64	$0.94	$0.56	$0.88	$0.42	$0.88	$1.25	$2.00
Range Minimum	$31.17	$38.66	$47.41	$38.73	$47.29	$31.43	$47.55	$45.62	$50.06
Range Maximum	$34.66	$42.95	$53.45	$42.28	$53.03	$34.20	$53.19	$53.36	$61.81

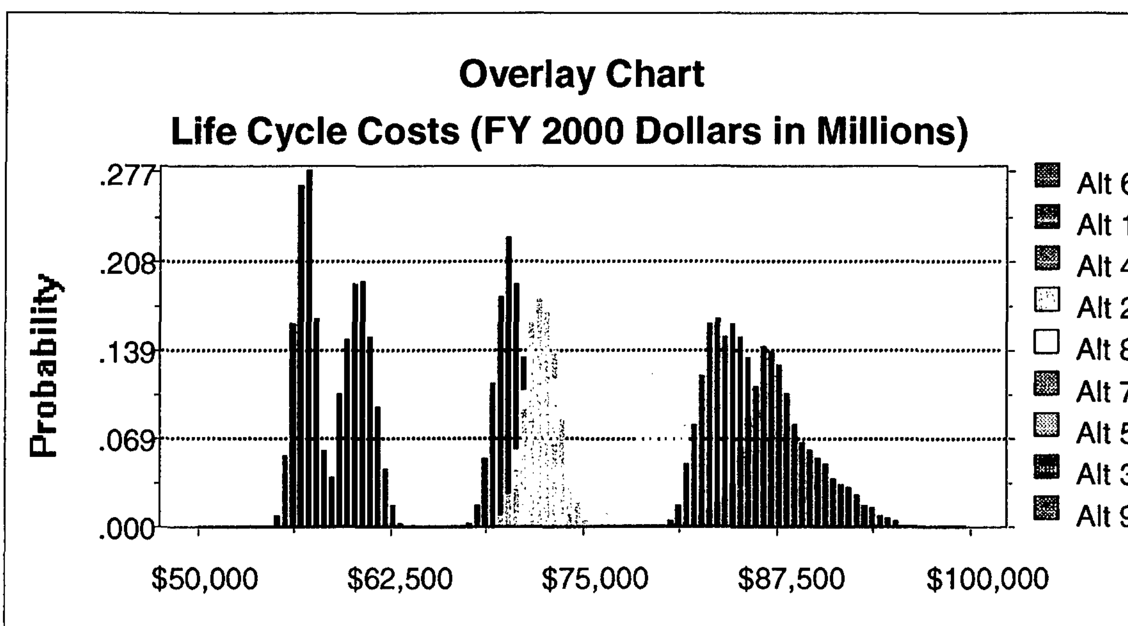

Figure 21. Life Cycle Cost Distributions—Constant Year Dollars

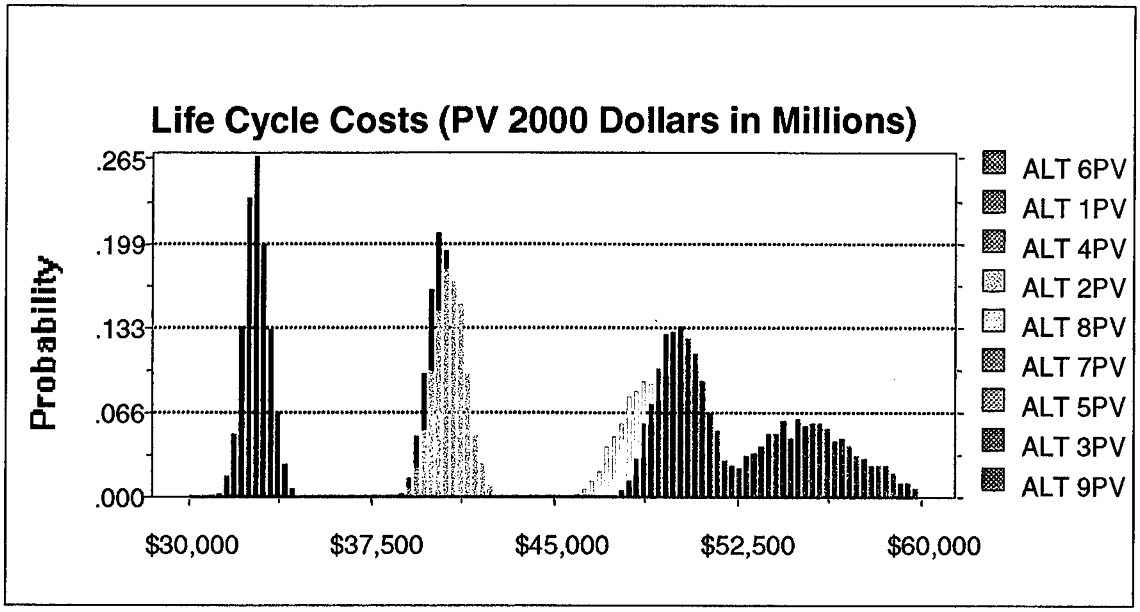

Figure 22. Life Cycle Cost Distributions—Present Value Dollars

Note that for both graphs, the LCC results fall into three main groups. For constant year dollars, the group costs means are approximately $60 billion, $70 billion, and $85 billion, with the latter showing the greatest spread. Also, within the lowest cost group, containing the "pure" C-5 fleets of Alternatives 1 and 6, the latter alternative (upgrade all C-5s) appears to be significantly lower than the baseline fleet of C-5s. The second group involves buying 20 C-17s, which augment the C-5 fleets of baseline (Alt 2) and upgrade C-5B only (Alt 4). Again, the latter alternative appears to be significantly lower than the alternative with the baseline C-5 fleet. For the third group, which involves buying from 45 to 132 C-17s, the lowest alternative is Alt 8, which is to buy 75 C-17s to be added to an upgraded C-5B fleet.

The present value graph (Figure 22) presents an interesting change in that for the first two groups, the differentiation between the competing alternatives within each group almost disappears. For example, whereas for the constant dollar case, Alt 6 is significantly lower than Alt 1, for the present value cases, the two distributions are nearly identical. On reflection, this is not suprising since Alt 1 has most of its cost spread out evenly over the life cycle period, while for Alt 6 there is the up-front cost of the RERP program. Therefore, the Alt 6 reduction in dollar terms due to discounting is not as great as for Alt 1, so the two distributions will become closer. Similar reasoning holds for the second group. For the third group, Alts 3, 5, and 7 (the +45 C-17 options) shift, on a relative basis, to the left (become lower cost) while the Alt 9 cost, buying 132 C-17s, stays very high because of the large up-front costs, which are not affected by discounting as much as the other alternatives.

One other point to note from the graphs is the relatively wide dispersion for Alt 9 because a significant portion (over 30 percent) of the total LCC is due to the C-17 acquisition. The procurement cost of the aircraft has a significant element of risk, with the airframe cost risk factor (as a multiplier of the best estimate) ranging from a low of 0.8 to a high of 1.25; the engine procurement cost risk factor ranges from a low of 0.72 to a high of 1.07.

Table 73 presents the cumulative distribution of life cycle costs for Alt 6, the lowest cost alternative, as determined from the simulation. These data can be used to provide the equivalent of confidence interval estimates for the life cycle cost. In this case, for example, we can say with "90 percent confidence" that life cycle costs will not exceed $57.9 billion, or we are 80 percent confident that LCC for Alt 6 will be between $56.1 and $57.9 billion.

Table 73. Percentiles of LCC for Alt 6

Percentile	Value
0%	$54,847
10%	$56,143
20%	$56,440
30%	$56,666
40%	$56,848
50%	$57,022
60%	$57,184
70%	$57,364
80%	$57,583
90%	$57,878
100%	$59,111

Results of the Cost Risk Analysis—Boeing Prices for the C-17. Table 74 presents the results of the cost risk analysis when prices proposed by Boeing are used for the C-17 procurement. Thus the only parameter changed is what the value of the most likely C-17 cost would be. All other parameters are unchanged from the analyses already discussed.

At the top of the table are the best estimates for the alternatives in both constant year and discounted dollars and the alternative rankings as determined by the constant year LCC. Note that the five lowest cost alternatives are the same as before, when IDA C-17 price estimates were used. However, there is a new order for the highest four alternatives, changing from 7-5-3-9 to 9-7-5-3; i.e., Alternative 9, buy 132 C-17s, moves from 9th place to 6th place. The first set of risk-analysis results is the rankings for the 9 alternatives using $FY00. As for the previous case, there is very high correlation between the best estimate ranking and that produced by the risk analysis. Again, we see that for the five lowest cost alternatives (Alts 6, 1, 4, 2, and 8 – in that order), there was not a single trial in which the alternative deviated from its comparative ranking. Of interest is the fact that when discounted dollars are used, Alt 9 reappears as the highest cost alternative—again, this is not totally unexpected since the cost stream for this alternative is heavily weighted toward the early years of the long life cycle period.

Figures 23 and 24 present the distributions of life cycle cost for the constant dollar and discounted dollar cases when Boeing proposed prices are used for the C-17 procurement.

The LCC results for this case fall into four main groups with Alt 8 now being in the third highest-cost group by itself, as there is very little overlap with the +20, +45, and +132 C-17 options. Note that the average LCC for the alternatives involving more than 20 C-17s are lower than the corresponding LCC values for the IDA estimate case by amounts ranging from $3 to $9 billion. As differentiated from the case using IDA prices, we see the results combine into four groups, the fourth group being Alt 8, the buy of 75 C-17s splitting away from the buy-45 and buy-132 alternatives. For constant year dollars, the group mean costs are approximately $60 billion, $70 billion, $75 billion, and $82 billion, with the latter group again showing the greatest spread. Also, within the lowest cost group, containing the "pure" C-5 fleets of Alternatives 1 and 6, the latter Alternative (upgrade all C-5s) appears to be significantly lower than the baseline fleet of C-5s. The second group again involves buying a 20 C-17s, which augment the C-5 fleets of baseline (Alt 2) and upgrade C-5B only (Alt 4). Again, the latter alternative appears to be significantly lower than the alternative with the baseline C-5 fleet. For the fourth or highest cost group, which involves buying from 45 to 132 C-17s, the lowest alternative is Alt 7, which is to buy 45 C-17s to be added to a fully upgraded C-5 fleet.

Table 74. Summary of Statistics of Cost-Risk Measures for the Life Cycle Cost Analysis Boeing C-17 Prices ($ Billions)

Statistic	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Alt 7	Alt 8	Alt 9
Best Estimate $FY00	$ 60.56	$ 71.30	$ 84.25	$ 69.09	$ 82.05	$ 56.78	$ 80.47	$ 75.30	$ 79.26
Best Estimate $PV	$ 32.92	$ 39.87	$ 47.92	$ 39.48	$ 47.53	$ 32.56	$ 47.56	$ 45.13	$ 48.55
Best Estimate Ranking $FY00	2	4	9	3	8	1	7	5	6
RANK COST RISK MEASURE	**Rank Alt 1***	**Rank Alt 2***	**Rank Alt 3**	**Rank Alt 4***	**Rank Alt 5**	**Rank Alt 6***	**Rank Alt 7**	**Rank Alt 8***	**Rank Alt 9**
Mean	2.00	4.00	9.00	3.00	7.98	1.00	6.80	5.00	6.22
Median	2.00	4.00	9.00	3.00	8.00	1.00	7.00	5.00	8.00
Mode	2.00	4.00	9.00	3.00	8.00	1.00	7.00	5.00	6.00
Standard Deviation	0.00	0.00	0.00	0.00	0.13	0.00	0.40	0.00	0.45
Range Minimum	2.00	4.00	9.00	3.00	7.00	1.00	6.00	5.00	6.00
Range Maximum	2.00	4.00	9.00	3.00	8.00	1.00	7.00	5.00	8.00
$FY00 COST RISK MEASURE	**Alt 1 $FY00**	**Alt 2 $FY00**	**Alt 3 $FY00**	**Alt 4 $FY00**	**Alt 5 $FY00**	**Alt 6 $FY00**	**Alt 7 $FY00**	**Alt 8 $FY00**	**Alt 9 $FY00**
Mean	$60.13	$70.89	$83.83	$68.78	$81.73	$56.54	$80.24	$75.39	$79.54
Median	$59.35	$70.87	$86.03	$70.33	$81.33	$57.84	$81.55	$74.84	$78.62
Standard Deviation	$0.98	$0.99	$1.00	$0.75	$0.76	$0.65	$0.67	$0.71	$0.84
Range Minimum	$56.93	$67.59	$80.43	$66.06	$78.90	$54.36	$77.92	$73.48	$77.72
Range Maximum	$63.24	$74.00	$87.04	$71.06	$84.00	$58.37	$82.09	$78.07	$83.08
$PV COST RISK MEASURE	**Alt 1 $PV**	**Alt 2 $PV**	**Alt 3 $PV**	**Alt 4 $PV**	**Alt 5 $PV**	**Alt 6 $PV**	**Alt 7 $PV**	**Alt 8 $PV**	**Alt 9 $PV**
Mean	$32.70	$39.67	$47.71	$39.31	$47.35	$32.42	$47.43	$45.17	$48.68
Median	$32.72	$40.83	$48.89	$40.12	$48.18	$33.09	$48.14	$45.15	$48.25
Standard Deviation	$0.53	$0.53	$0.53	$0.39	$0.40	$0.34	$0.35	$0.37	$0.43
Range Minimum	$30.99	$37.90	$45.89	$37.89	$45.88	$31.25	$46.19	$44.17	$47.71
Range Maximum	$34.37	$41.34	$49.43	$40.54	$48.57	$33.38	$48.42	$46.63	$50.52

The present value graph (Figure 24) again presents an interesting change in that, for the first two groups, the differentiation between the competing alternatives almost disappears. Perhaps more interesting is the shift of Alt 9 from fourth highest to highest when present values of LCC are used, which has been mentioned earlier.

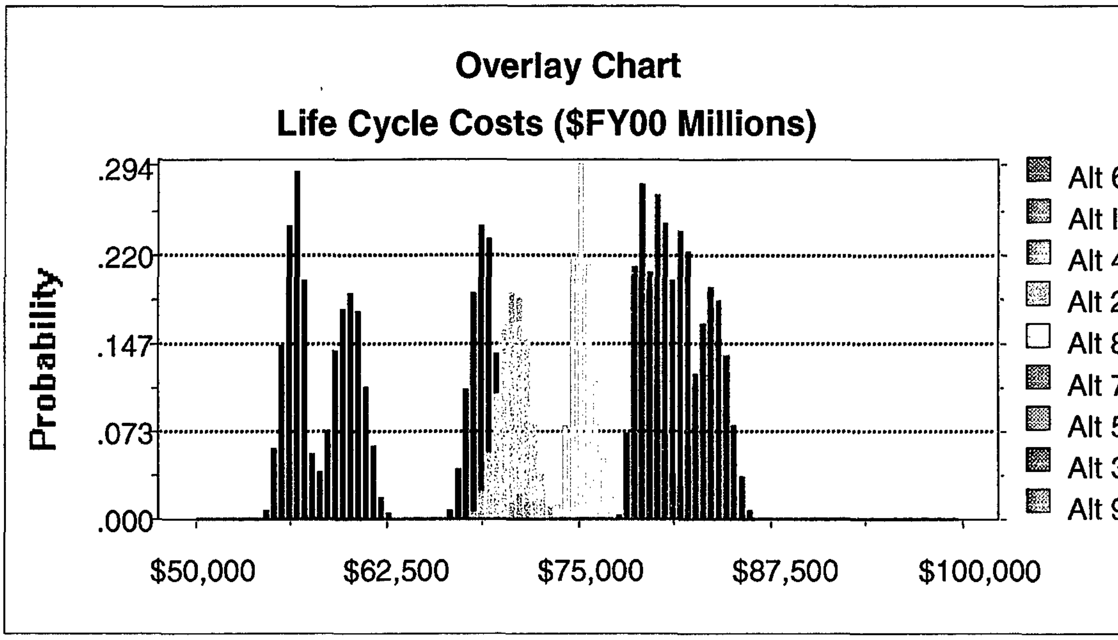

Figure 23. Life Cycle Cost Distributions, Boeing C-17 Prices—Constant Year Dollars

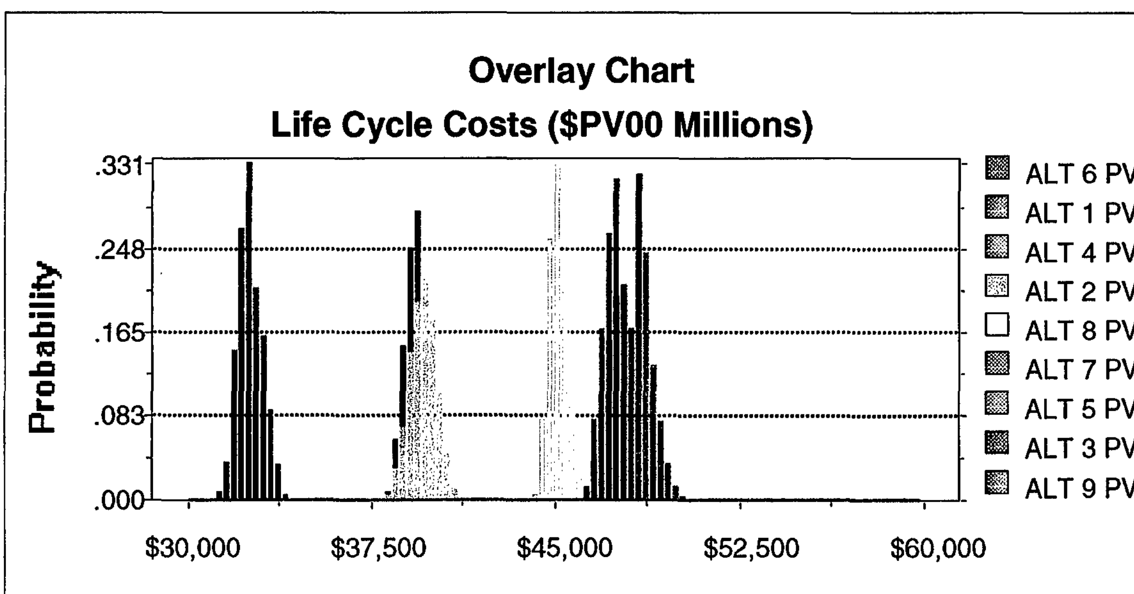

Figure 24. Life Cycle Cost Distributions, Boeing C-17 Prices—Discounted Dollars

e. Summary of the Cost Risk Analysis

The cost risk analysis confirms results based solely on the best single-point cost estimates. For both the IDA C-17 prices and Boeing prices, Alternative 6 is the lowest cost alternative, and significantly lower than Alternative 1 when constant dollars are used. For the Present Value case with discounted dollars, however, Alternatives 1 and 6 exhibit comparable risk distributions with considerable overlap.

Part 3

ANALYSES

I. STRUCTURAL ANALYSES

Aircraft such as the C-5 and C-17 undergo extensive stress during their daily and wartime activities. For that reason we take a look at the fatigue limits expected for both aircraft and at the costs associated with maintaining their flying capability through 2040. The C-5 airframe is older than that of the C-17. Because AMC plans to fly the C-17 at such a greater number of flying hours per year than the C-5, the aging of both aircraft over this long period of time is an area for analysis.

A. C-5 STRUCTURES

1. Introduction

A key issue in the analysis of any aircraft upgrade option is the viability of the airframe structure for the time period under consideration. This study contemplates C-5 service to year 2040, a considerable extension beyond the aircraft's originally anticipated retirement date.

We used three steps to evaluate the structure's fitness for this extended service life. First, we used test results to determine whether the overall structure could reasonably be expected to achieve the flight hours required without failure of major structural components. In general, our analysis assumes that if a component were tested to twice the expected service life, without structural failure, major failures in service would be unlikely. The factor of two inherent in this analysis is consistent with service experience and statistical analysis. Thus we selected as the structural life one-half of the test-demonstrated life as a low risk estimate.

Second, we examined cases where the overall structure is suitable for extended life, but where test results or service experience indicate that retrofits of subcomponents are likely to be required. We assigned costs to these retrofits, to be expended in a year consistent with the estimated life of the subcomponent.

Third, we extrapolated the results of our near-term projections to the outyears of the study's 2040 timeframe. This extrapolation is an acknowledgement that service experience will continue to produce unexpected failures at the subcomponent level, even while the major structure remains sound. Specifically, we assumed that the annual retrofit costs in years 2025-2040 would be equal to the average retrofit costs for years 2005-2024.

2. Results

We found that the major fuselage and wing structure of the C-5 fleet is capable of reaching the year 2040 if flown at current flight hour rates and at current severity levels. Figure 25 summarizes the projected number of C-5A and C-5B flying hours and those expected from now until 2040. The upper-wing surface fatigue limit shown in Figure 25 is the 65,000 Wing Mod Design flight hours, reduced by a factor two and multiplied by a factor of 1.47, the ratio of actual flying hours to the wing mod design hours. As Figure 25 shows, the projected use will not exceed the fatigue limits before FY 2040.

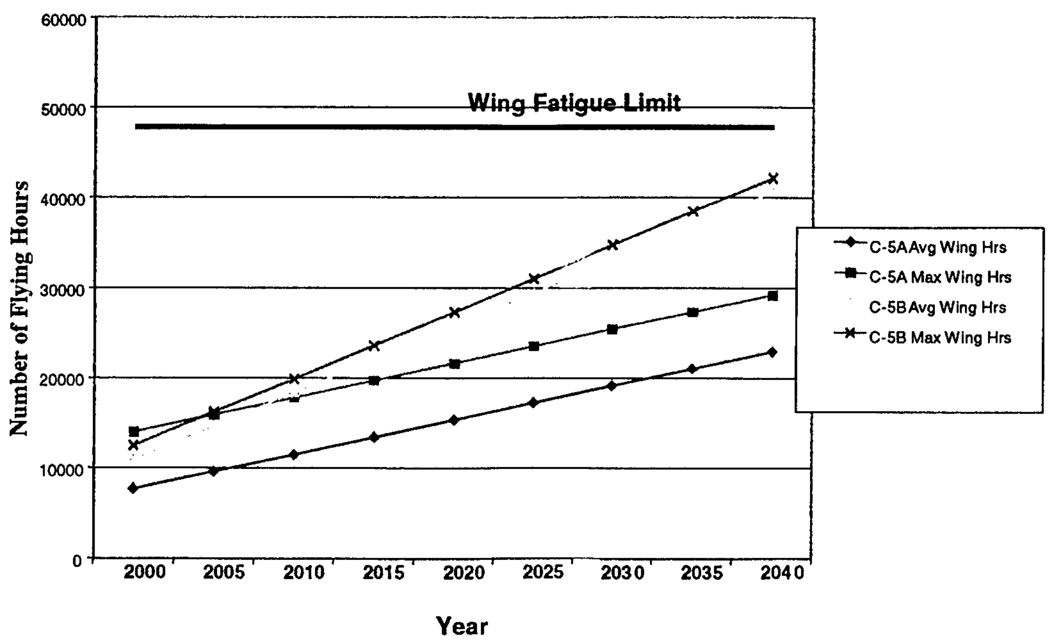

Figure 25. C-5 Projected Flying Hours

The C-5 fuselage was tested to 16,960 pressure cycles before test termination. Our assessment places the pressure cycle fatigue limit at one-half this value, or 8,480 cycles. This fatigue limit is shown in Figure 26, along with the projected number of cycles that the C-5s will undergo through the year 2040, if flown at current rates and severity levels.

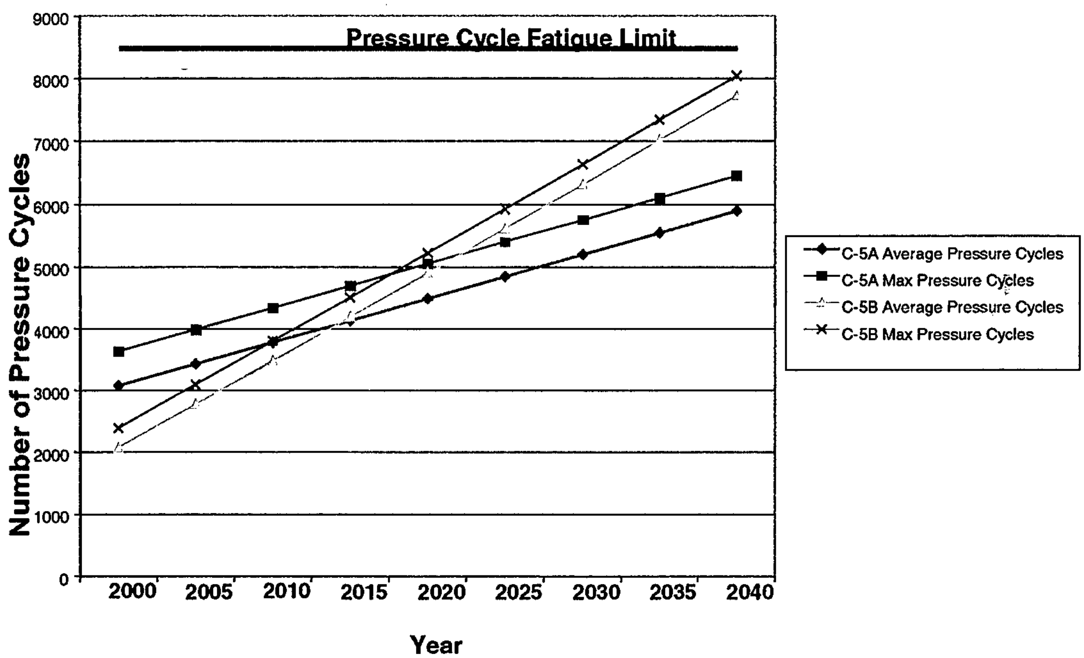

Figure 26. C-5 Projected Fuselage Pressure Cycles

Despite these encouraging observations, the aft-fuselage upper crown skin and the horizontal stabilizer will require significant retrofits. Landing usage will also increase the cost of depot maintenance as landing gear parts increasingly reach service life limits, starting about 2030. Wing trailing edge flaps and engine pylons are also likely to require retrofits before completion of the required year 2040 service life. None will limit the life of the C-5, but each will require retrofits with associated costs.

A summary of the C-5 retrofit items and unit costs is shown in Table 75. Some costs are sensitive and cannot be reported in the current document. A detailed description of the analysis and results is available in Volume II, Appendix A of this report.

Table 75. C-5 Structural Retrofits Needed to Ensure Operations through 2040

Structural Retrofit Needed	Cost per C-5 Aircraft (FY 2000 $K)	Retrofit Begins in FY
Horizontal Tail Aft Fitting (Interim)	*	1999
Horizontal Tail Aft Fitting (Replacement)	*	2004
Horizontal Tail Forward Fitting	*	2014
Upper Crown Skin	*	2004
Engine Pylons	1,200	2010
Trailing Edge Flaps	1,000	2010
Landing Gear	500	2030

* Estimate is derived from proprietary information. Appendix A, Volume II contains this data.

B. C-17 STRUCTURES

1. Introduction

Calendar year service extension to 2040 is not as lengthy for the C-17 as it is for the C-5, but the C-17 will be flying very high flying hour rates. By the year 2040, these rates will bring the fatigue use of the fleet to levels comparable to the C-5. In addition, some elements of the program's history raise specific concerns that must be addressed when contemplating the cost of a long service life.

We used the same three steps of analysis for the C-17 that we did for the C-5. We used test results to establish the service life of the overall structure, followed by analysis of individual areas likely to require retrofit, including extrapolation of near-term results to calculate outyear retrofit costs.

2. Results

At current flying severity, and at the flight hour rates assumed in our study, the overall C-17 structure is likely to reach year 2040 without widespread failure of the major wing and fuselage structure. The C-17 fatigue test article applied 90,000 flight hours of flight loads to the wing structure, a test that was completed without major structural failure. By incorporating the reduced severity of historical C-17 use and dividing by 2, we find that the low-risk fatigue lifetime for the C-17 wing is 56,250 flying hours. Based on current flying hour programs for the C-17, the wing will begin to reach this threshold in 2035. Figure 27 shows this projection, along with the fatigue limit noted.

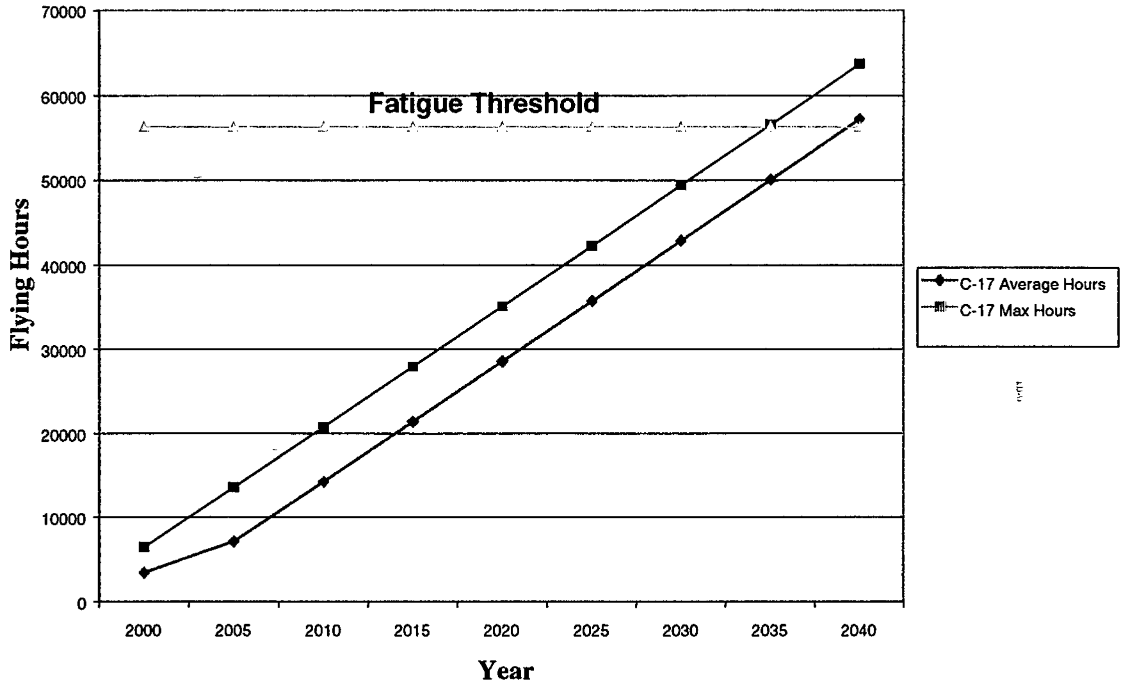

Figure 27. C-17 Projected Wing Hours

The corresponding test-demonstrated fuselage pressure cycles is 40,000 cycles. We put the fatigue life at 20,000 cycles and show a comparison of the projected number of cycles relative to this limit in Figure 28. The reason for this very large limit appears to be the use of long-range vice short-range tactical-mission flights. This will lengthen the fuselage life beyond that originally planned. As Figure 28 shows, none of the aircraft will exceed the threshold before 2040.

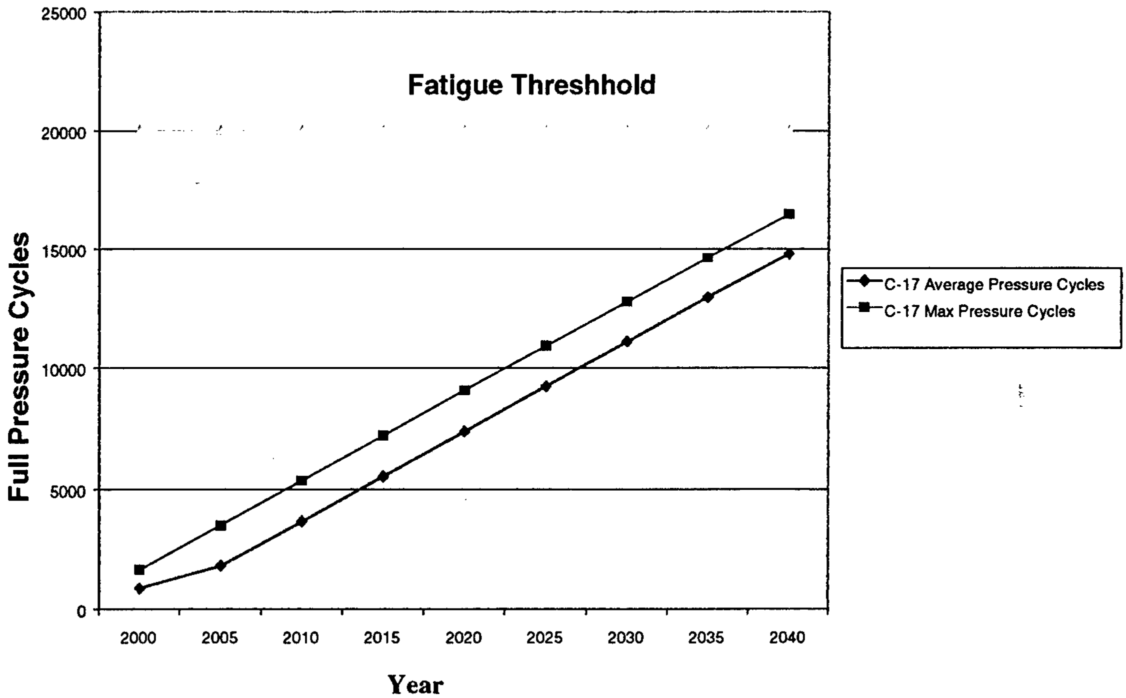

Figure 28. C-17 Projected Fuselage Pressure Cycles

However, the ongoing testing and early service life results indicate that investments will be required to achieve this service life goal. The fuselage achieved a large number of pressure cycles, but did experience some failures of the aft bulkhead and aft frames that would require remedy to achieve full-service life. Retrofits are also likely for the fuselage jack fittings, which have already had three in-service failures. The landing gear has not completed its fatigue testing, but has had several failures in the testing that has been completed. More failures in testing can be expected. The horizontal tail is likely to require retrofits because the high loads seen during aerial refueling will substantially reduce its fatigue life, particularly in the metal structure to which the new composite horizontal tail is attached. The engine pylons are also experiencing high aerial refueling loads and are therefore likely to need retrofits before the end of the year 2040 analysis period.

A summary of the projected C-17 retrofit costs is shown in Table 76. A more detailed discussion of the C-17 retrofit analysis is available in Volume II, Appendix A.

Table 76. C-17 Structural Retrofits Needed to Ensure Operations through 2040

Structural Retrofit Needed	Cost per C-17 Aircraft (FY 2000 $K)	Retrofit Begins in FY
Fuselage Bulkhead	100	2015
Fuselage Frames	200	2026
Fuselage Jack Points	75	2000
Landing Gear (major)	130	2014
Landing Gear (minor)	50	2010
Horizontal Tail	390	2020
Engine Pylons	500	2015

C. SUMMARY

A summary of C-5 and C-17 total retrofit costs, including extrapolations through FY 2040, is shown in Table 77 for each of the study's force alternatives. The costs are in constant FY 2000 dollars.

Table 77. Retrofit Cost of Alternatives to Ensure Operations through 2040

Alternative	Number Additional C-17s	Number C-5s	C-17 Retrofit Costs (FY2000 $M)	C-5 Retrofit Costs (FY2000 $M)
1	0	126	0	588
2	20	126	38	588
3	45	126	88	588
4	20	126	38	518
5	0	126	0	518
6	0	126	0	411
7	0	126	0	411
8	75	50	143	215
9	132	0	252	23

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II. MISSION CAPABLE RATE ANALYSES

A. BACKGROUND

1. Mission Capable Rate (MCR)

The Air Force uses aircraft mission capable rate to describe the operational readiness of its aircraft fleets. There three primary levels of readiness: full mission capable (FMC), partially mission capable (PMC) and not mission capable (NMC). An aircraft that can do at least one but not its entire set of assigned missions is PMC. MCR is the long run or steady-state proportion of the operational (possessed) fleet that is FMC or PMC. Mission capability is defined by the state of the aircraft systems and subsystems. The Minimum Essential Subsystems List (MESL) defines the systems and subsystems that must work for the aircraft to do its assigned missions.

The operational fleet to which the MCR metric applies are those aircraft in the Primary Aircraft Inventory (PAI). Such aircraft are termed "possessed." This excludes Backup Aircraft Inventory (BAI), those aircraft currently "owned" by maintenance activities to perform scheduled or unscheduled maintenance, modifications, inspections, and repair. Thus, aircraft undergoing Program Depot Maintenance (PDM) or major modification using a depot field team are BAI and not possessed.

We first developed MCR estimates for each of the C-5 configurations defined for this study under peacetime conditions: flying program, maintenance manpower, maintenance policy. We then adjusted these estimates for the wartime environment. Both conditions will be described in turn.

2. Mission Capable Rate Relationships

In its simplest form, if data at the aircraft level are collected on a fleet of aircraft over a fixed time period, the mission capable rate can be determined by equation II-1,

$$MCR = 1 - \left(\frac{Total\ Not\ Mission\ Capable\ hours}{Total\ possessed\ hours}\right). \qquad \text{(II-1)}$$

The numerator, total not mission capable hours, or downtime, is relatively easy to measure at the aircraft level but is very difficult to model, especially at the subsystem and equipment levels. This is especially true when one considers the types of data that are generally available through Air Force data systems. Mission capable rate combines failure frequency with repair efficiency and thus is dependent on reliability and maintainability parameters. But, many other factors affect the mission capable status of an aircraft. For example, if a part needed to repair a failed component is not available, then the resulting logistics or supply delay adds to the down time. Therefore, having repair times on components or subsystems is not sufficient for modeling downtime due to failure of the item. No trouble found (NTF) actions do not generally trigger the supply system but do result in a NMC coding if the item is considered to be mission essential. Scheduled maintenance activities also result in a NMC status. Typically, the C-5 aircraft undergoes periodic Home Station (HS) checks and isochronal inspections. Since the aircraft remains in a possessed status during such scheduled maintenance, it is recorded as NMC over the maintenance period.

3. Contributors to Not Mission Capable Rate

As indicated above, an aircraft can be in a not mission capable status for a number of causes. Listed below are the NMCR categories we used, a downtime taxonomy if you will, which enabled us to deal with both scheduled and unscheduled corrective maintenance as well as other causes of down time of possessed aircraft.

Failures—This category represents the downtime resulting from failures of critical components or subsystems. It is the primary cause of not mission capable time and is the NMCR component for which the simulation model was developed.

Isochronal Inspections—This is a scheduled maintenance activity performed at the operating base approximately every 400 days and is designed to keep the aircraft healthy and safe.

Home Station Checks—This is also a scheduled maintenance activity performed every 90 days and is also done to ensure the aircraft is healthy and safe.

Other Non-Corrective Maintenance—These are generally inspections and maintenance activities performed to meet special conditions or emergencies and which have not been included in the other non-corrective maintenance schedules. An example might be discovery of a serious safety problem such as a crack in a structural member resulting in a directive to inspect all aircraft that may be subject to the same problem.

Refurbishments—These are activities performed on-base to maintain the aircraft in an operable state. They might include such activities as washing, painting, and minor corrosion repair.

Cannibalization—Typically, for the C-5 fleet, there is a "cann bird" at each major C-5 operating base that acts as a source of parts supply. A part needed to restore an aircraft to mission capable status after returning from a mission is borrowed from the cann bird if it is not available from supply. When the part is received through the logistics supply chain at the base, it is used to fill in the hole in the cann bird. All such time that the cann bird has missing critical parts, it is not mission capable time since the aircraft is considered to be possessed.

4. Prior C-5 Modernization Studies and MCR

In 1996, the Air Force awarded a contract to the Lockheed Martin Corporation to evaluate potential improvements to the C-5 aircraft and aircraft logistics system. Two interim reports and a final report[1] were produced, the latter identifying a comprehensive modification package "which brings the aircraft to substantially improved levels of departure reliability and mission capable rate." The final report in December 1996 evaluated the effect of reliability improvements on MCR by assuming that overall system MCR is linearly related to the sum of the subsystem improvements. For example, if a

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1 *C-5A/B Modernization Study, Phases I-III*, Lockheed Martin Aeronautical Systems, 1996, PROPRIETARY.

particular subsystem was responsible for a 5-percent Not Mission Capable Rate, and modernization improvement reduced that subsystem's failure rate by 80 percent, the overall system NMCR would be reduced by 0.8 x 5 percent, or 4 percent. Under this methodology, evaluating the effect of a series of subsystem improvements would only require the summation of the proportional improvements in each subsystem.

In late 1997 IDA conducted a review[2] of the aforementioned study for the Air Mobility Command and the Office of the Secretary of Defense and introduced a more sophisticated way of viewing the impact of failures. Our work showed that the way in which system downtime is recorded creates an effect we call masking. Masking makes summation of subsystem NMCR improvements an inaccurate method for calculating system NMCR improvement. This phenomenon is explained next.

NMCR data are recorded for only one component in any given aircraft down period. If the plane is down for 10 hours because of an engine problem, all of the other repairs done at that time go unrecorded as NMCR contributors as long as their repair time is less than 10 hours. This has the effect of understating the actual reliability impact of most of the aircraft's subsystems, creating the masking that distorts linear NMCR improvement analysis.

In a simple example, assume that component A has a mean repair time of 8 hours, and a failure rate of 0.5 times per flight. Assume that component B has a mean repair time of 7 hours, and a failure rate of 0.5 times per flight. The contribution of component B to NMCR will be understated by the data because, for many of the flights where component B fails, component A will fail as well, so that component B is not credited with the downtime. If component A is modernized so that its failure rate is improved to 0.05 times per flight, its improved reliability will reveal more of the actual failure rate of component B. Calculations showing this effect are shown in Table 78. The analysis assumes that there is one flight per day, so that the NMCR created by 1 hour of repairs after a flight equals 1/24 or 4.2 percent.

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2 *Independent Analysis of C-5 Modernization Study*, IDA Paper P-3371, December 1997, UNCLASSIFIED/PROPRIETARY, as well as *Redacted Version of Independent Analysis of C-5 Modernization Study*, IDA Paper P-3454, December 1997, UNCLASSIFIED.

Table 78. Example of Component Failure Overlap and Masking

Item A:	Failure Probability			0.5
	Mean Repair Time=			8
	Modernized Failure Probability=			0.05
Item B:	Failure Probability=			0.5
	Mean Repair Time=			7
Event	Baseline Failure Probability	Baseline Expected Repair Time	Modernized Failure Probability	Modernized Expected Repair Time
A&B Fail	0.25	2	0.025	0.2
A Fails	0.25	2	0.025	0.2
B Fails	0.25	1.75	0.475	3.325
No failure	0.25	0	0.475	0
Total System		5.75		3.73
System NMCR		24%		15%

Note that in the baseline, component A is being credited with 2 hours of expected repair time, while component B is credited with 1.75 hours of repair time. This accounting reflects the manner in which G081 data records component contributions to aircraft downtime. After modernization, the downtime credited to item B increases, even though no change was made to item B reliability.

If this data were treated linearly, the 90-percent improvement in component A reliability would produce an NMCR improvement corresponding to 90 percent of component A's recorded downtime. Or,

$$\text{Modernized NMCR} = ((0.1)*4)+1.75)/24 = 8.9\%. \qquad \text{(II-2)}$$

That is, instead of a change of NMCR from 24-15 percent, the linear analysis would have predicted a larger reduction of NMCR to 8.9 percent. The linear analysis used by Lockheed seriously overstates the NMCR improvement that would be expected through the improvement of an individual component.

Simple mathematical accounting of the type illustrated would be impractical for a system as complex as the C-5 with numerous components, so we accounted for the effect of masking by creating a simulation of the C-5 system. The simulation uses Monte Carlo random draws on more than 200 individual components to model the reliability of the system, before and after reliability improvements. The results we produced in our original 1997 review[3] of the Lockheed C-5 modernization study, compared to the results of a linear analysis, are shown in Figure 29. Note that for the linear method, the NMCR of Other Subsystems remains unchanged after the improvement but it increases because of unmasking using the simulation method. The net effect is that the estimated improvement using the linear method is optimistic. For the current study, we added many refinements and additional capabilities that will be outlined in the following pages.

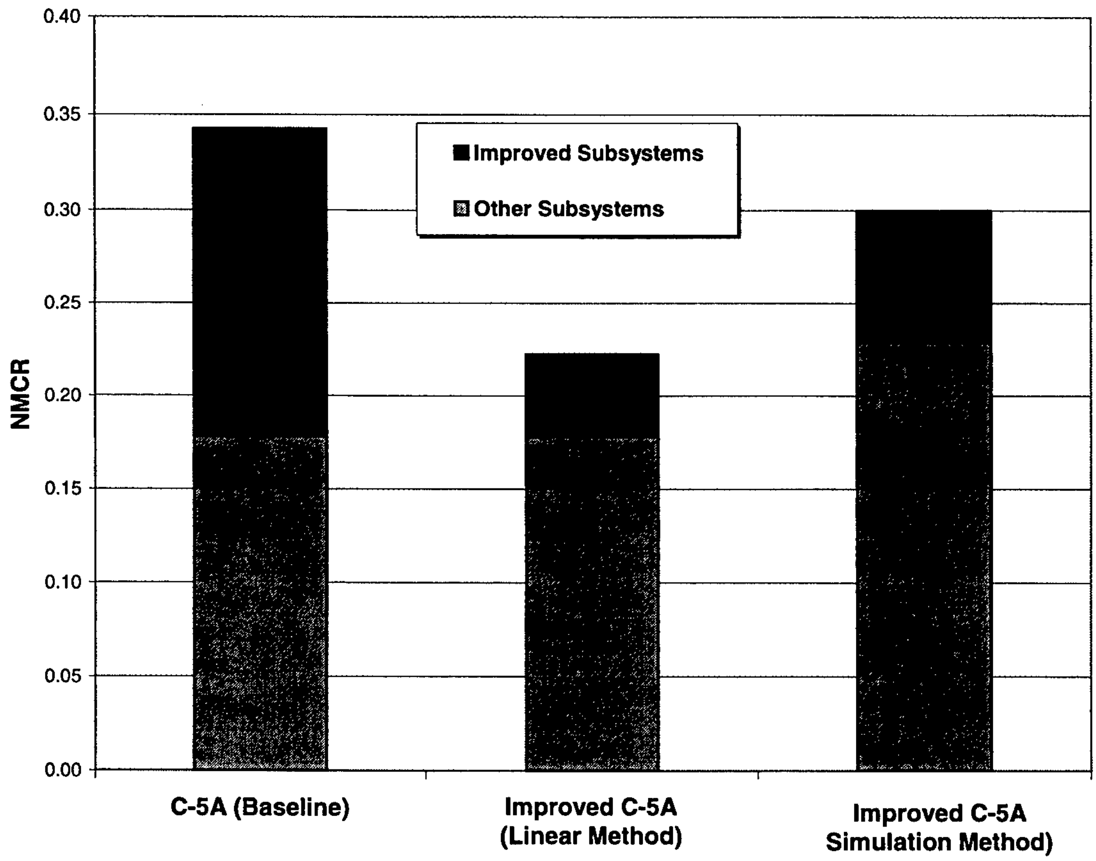

Figure 29. Comparison of Results of Different Improvement Calculations

3 Ibid.

B. CORRECTIVE MAINTENANCE BASIC SIMULATION METHODOLOGY

1. Subsystem Failure Simulation

The IDA NMCR model calculates system corrective maintenance NMCR by simulating failure patterns for each of more than 200 subsystems. For each of these subsystems, the model uses reliability data to determine the probability of failure on a given flight. The model uses historical maintenance man-hour data to estimate the distribution of repair times when failures occur. A random draw simulation uses these failure probabilities and repair time distributions to determine which subsystems fail on a given flight, and how long it will take to repair each of these subsystems. The total system repair time is then calculated by summing the subsystem repair times, including assumptions concerning serial or parallel repairs. This process is repeated 10,000 times, the number of times for stability in the Monte Carlo results to manifest itself (see the Verification and Validation analyses at the end of this appendix). The average repair time produced by these iterations, divided by the time between takeoffs, is the not mission capable rate.

Figure 30 shows schematically the simulation approach.

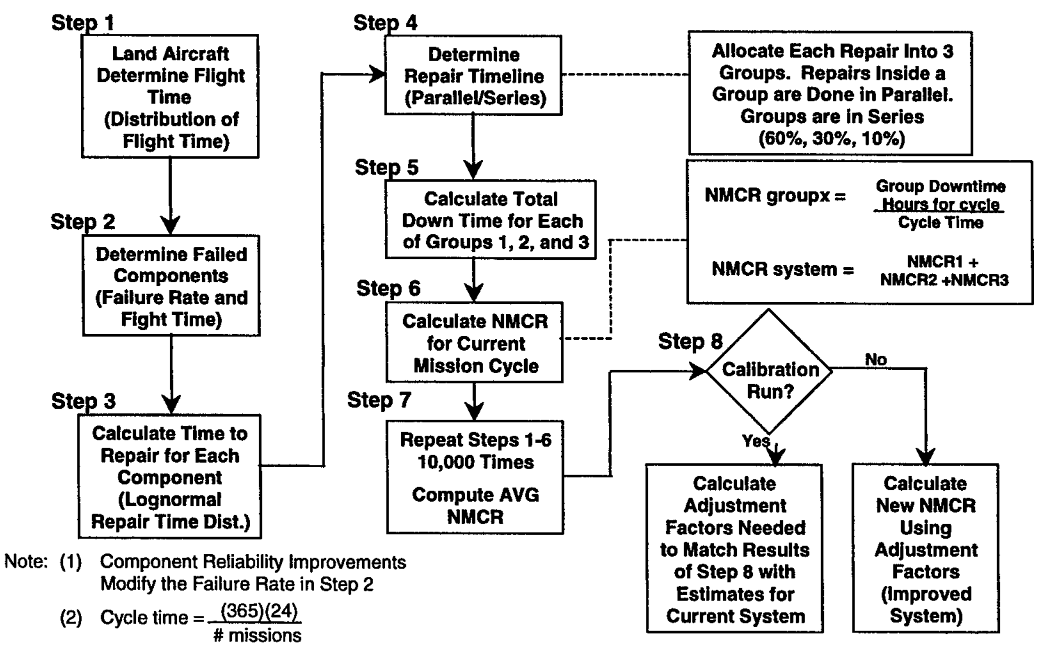

Figure 30. MCR Simulation Process

2. Individual Component Failures

We used USAF G081 failure data at the three-digit work unit code (WUC) level to build our subsystem model. The three-digit data resulted in a list of 240 subsystems for the C-5. Thirty-two of these subsystems were candidates for reliability improvement in the Lockheed C-5 modernization study. The refined analysis of this study added 20 items to the list of the previous study, by breaking avionics into 21 separate subsystems. This resulted in 260 subsystems overall, with 53 of these subsystems candidates for modernization.

For each of these subsystems, we used historical data to determine the failure rate, expressed as events per 1,000 flight hours. For components whose failure propensity was primarily time dependent (as opposed to sortie dependent), the failure rate was converted to a failure probability on a given flight, using the assumption that failures would occur according to an exponential failure distribution. The probability of failure on a given flight became:

$$P_f = 1 - e^{-t/\theta}, \tag{II-3}$$

where P_f *is* the probability of failure on a given flight, t is the duration of the flight, and θ is the mean time between failures, the reciprocal of failure rate. See the discussion below for sortie dependent failures.

The model uses this probability to determine whether a failure has occurred on a given simulation iteration or flight. It does so by simply picking a random number between zero and one. If the random number is less than the probability of failure, the subsystem has suffered a failure for that iteration.

3. Sortie Dependent Failures

Another adjustment to the underlying model concerned items whose failures depend more on numbers of sorties than on the mission duration. Good examples are landing gear and brakes. The number of landing gear failures over any period of time is much more dependent on the number of landings (sorties) than on the total flying time over the period. For sortie dependent subsystems, identified by AMC/LGAA, we divided the total number of failures contained in our data base by the number of sorties over that time period to calculate a sortie failure probability. This is in lieu of developing an MTBF estimate and then applying the exponential distribution to mission flying hours.

4. Downtime

Once a subsystem fails, it was then necessary to determine the time required for completing the repair. We assumed that repair times were distributed according to a lognormal probability function. We used man-hours from the G081/REMIS data as a surrogate for the mean downtime for each subsystem. We recognize that this is an imperfect surrogate, but its use was necessary because we were unable to obtain historical data for downtime at the three-digit level. Because the model is calibrated to historical data, the use of man-hours will only introduce serious errors when the relationship between man-hours and downtime varies significantly from one subsystem to another.

In addition to requiring a mean repair time, our simulation required a distribution about that mean. We assumed a repair time standard deviation equal to 30 percent of the mean repair time. This produced a distribution of repair times that was consistent with the experience of C-5 maintenance personnel.

Given a mean, a standard deviation, and a lognormal distribution for each subsystem, we were able to determine a repair time for each iteration of the simulation. Combining these subsystem repair times to compute a system repair time required consideration of the extent to which repairs of separate subsystems could be done in parallel.

5. Parallel vs. Serial Repairs

When an airplane lands with multiple failed subsystems, it is clearly possible to begin repairs on several subsystems simultaneously. The extent to which this can be done depends on many factors, including available manpower, physical space constraints, subsystem interdependence, and safety considerations. Not all repairs are or can be conducted simultaneously. Experience shows that many are repaired sequentially.

We modeled the effect of parallel (simultaneous) and sequential repairs by assigning each failed subsystem to one of three repair bins. All subsystems assigned to the first bin would all be repaired in parallel. All items in the second bin would be repaired in parallel with each other, but only after the completion of repairs from the first bin. Similarly, items in the third bin are worked on only after all items in the second bin are repaired.

Subsystems were assigned to a bin using probabilities and a random number draw on each iteration. We assign bin probabilities of 60 percent to bin one, 30 percent to bin

2, and 10 percent to bin three. These probabilities mean that 60 percent of the subsystems will be assigned to the first bin, 30 percent to the second, and 10 percent to the third. Increasing the percentage of subsystems assigned to the first bin implies increased manpower, shortened system restoration times, and reduced NMCR. The percentages we chose were consistent with the experience of maintenance personnel and also produced NMCR values that approached historical values without excessive factoring.

There is one exception to the random binning concept—mandatory sequential repair operations. AMC/LGAA provided information about those components and subsystems for which parallel repair would be not likely take place because of safety or accessibility reasons. An example would be the fuel system. Since our analysis was at the three-digit WUC level, each of which includes a number of components, the information provided by AMC/LGAA was used to assign binning percentages to each WUC. Thus the value of 40 percent for WUC 46A (Tank Fuel Storage) can be interpreted to mean that 40 percent of the failures in that WUC are subject to parallel repair. In the simulation model, we created two subsets of components by dividing the failure rate proportionally—one subset subject to binning and the other not.

6. Mission Essential Items

We used the Minimum Essential Subsystem List (MESL) to identify those subsystems determined by the Air Force to be critical for completing the C-5 mission. This list defines criticality for several specific missions, e.g., Rolling Cargo-Airland, as well as having a Full System List (FSL) designation. We used the latter to define criticality. We eliminated 66 subsystems out of the original 260 from the MCR analysis based on mission criticality.

7. Type 6 Failure Events

Type 6 failure events are those for which a complaint is made but the maintenance technician cannot find the problem, e.g., it is a no-trouble-found or cannot duplicate assessment. While these failures do not normally consume material, they do account for downtime. It is unclear how to deal with such events in this analysis because we were informed that Type 6 occurrence rates are often much overstated. We decided to use a 50 percent factor, i.e., we counted 50 percent of the Type 6 failures in developing the subsystem failure rates. Subsequent sensitivity analysis showed that the results were relatively insensitive to this percentage as long as it was applied across the board.

8. Calculation of NMCR

NMCR can be calculated after determining repair times and serialization. The total repair time for iteration is the sum of the repair times from each of the three repair bins. The repair time for each bin is simply the maximum repair time of any subsystem assigned to that bin which failed on that iteration. In other words, System Repair Time = max (repair times of Bin One subsystems) + max (repair times of Bin Two subsystems) + max (repair times of Bin Three subsystems).

NMCR is simply the system repair time divided by the time between each mission takeoff. This time is equal to the flight time of the first mission, plus the repair time after that mission, plus the non-utilized mission capable time between missions.

The system NMCR is determined by iterating the simulation 10,000 times. Sensitivity studies showed (see Section F) that this number of iterations was required before the calculated NMCR became stable.

9. Calibration to Historical Data

We recognized that our bottoms-up simulation contained assumptions and simplifications that could preclude the direct accurate estimation of aircraft NMCR. However, the goal of our model was to estimate the effect of subsystem reliability improvement on the overall aircraft NMCR. The model's estimation of relative system improvement was only compromised to the extent that the impact of the introduced errors varied from one subsystem to the next.

We calibrated the model to previous history for two reasons. First, although intended to measure relative improvement, our model would be used to project future NMCR for the C-5 system. Calibration to previous history would allow the model to be used in this way. Second, the degree of factoring required to match historical results would give some indication of the degree to which our assumptions or data had introduced errors into the analysis.

Calibration was achieved by multiplying the mean repair time by a calibration factor until the simulated aircraft matched the historical NMCR values. After we calibrated the baseline configuration, we adjusted the reliability of individual subsystems to reflect modernization improvements. We ran the simulation again to calculate NMCR with modernized subsystems.

10. Improvements since the 1997 IDA Study

Work in the current AoA task added a series of improvements to the model[4] created for the initial modernization study. These improved both the fidelity and the flexibility of the model, making it more suitable for the MCR analyses required for the AOA. The most important of these improvements were the modeling of the C-5B, simulation of a wartime environment, and inclusion of a more detailed subsystem list.

The current model includes an entirely independent analysis of the C-5B, while the previous model modified C-5A results to obtain C-5B modernization improvement. Repair and reliability data do show differences between C-5A and C-5B aircraft, most dramatically in the repair time numbers, so this was a significant improvement in the model.

The current model also simulates a wartime environment and includes different surge and sustain period assumptions for scheduled maintenance, serial repair time, sortie length, utilization rates, and mission critical subsystems.

Subsystems included in the AMP upgrade are modeled as 21 individual items with separate reliability and repair time statistics. The previous model included these as one avionics upgrade line item. Other refinements included more rigorous accounting of subsystem failure rates, removal of scheduled maintenance from the calibration baseline, and the use of updated reliability data.

C. DETAILED METHODOLOGY, ASSUMPTIONS, AND DATA SOURCES

1. Aircraft Configurations

To apply the model to the C-5 portion of the O&O AoA, we need to develop mission capable rate estimates for those aircraft configurations that, when appropriately combined, lead to an estimate of MCR for each of the alternatives under consideration. There are five basic C-5 configurations, which are listed below:

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4 *Ibid.*

- **Current**—This is the current fleet for which the historical data apply. While this configuration does not appear in any of the AOA alternatives, we need to consider it in order to perform the model calibration, and it represents a point of departure for developing the other configuration MCRs.
- **FY04 Configuration**—This is the baseline aircraft configuration after all modifications planned for FY 2000-FY 2004 are implemented. These improvements include completing the TF39 engine upgrade (the so-called HT90 upgrade) and thrust reverser upgrades as well as the installation of a new avionics suite—the C-5 Avionics Modernization Program (AMP).
- **FY04 Baseline with Letter Check**—This is called the Baseline C-5 Configuration, which has the FY04 baseline aircraft as well as a different scheduled maintenance concept, namely one involving the so-called letter check principle, which combines isochronal inspections, refurbishments, and PDM into an annual scheduled maintenance program.
- **Partial Upgrade with Letter Check**—This is called the Partial Upgrade C-5 Configuration for which the aircraft are an upgrade from the FY04 baseline configuration, having all additional C-5 modifications being proposed by Lockheed except for the replacement of the propulsion system
- **Full Upgrade with Letter Check**—This is called the Full Upgrade C-5 Configuration, for which all C-5 modification proposed by Lockheed in the Phase III Modernization Study[5] are implemented, including the replacement of the propulsion system.

2. Description of Input Data

To implement the MCR model, a wide variety of data sources are needed to develop the necessary reliability, maintainability, and programmatic factors. In many cases more than one data source was used, either to fill-in holes, to "average-out" anomalies, or to confirm results. The primary source for the historical MCR and R&M data that were used was Logistics Branch of the Air Mobility Command (AMC/LGQA). Data of this type came primarily from the G081 and REMIS data systems, herein referred to as G081/REMIS, much of which were summarized in a C-5 historical data file maintained by AMC, herein referred to as C-5HistDB. Additional data were provided by the Logistics personnel at Dover Air Force Base and other Air Force organizations such

[5] *C-5A/B Modernization Study, Phases I-III,* Lockheed Martin Aeronautical Systems, 1996, PROPRIETARY.

as AFOTEC and the Air Force Cost Analysis Agency. A summary of the major types of data used and their primary sources is presented in Table 79.

Table 79. Summary of Major Types of Data Used in the MCR Model

Type of Data	Primary Source	Description	Period	Use
Flying Hour and Fleet Sizes	AMC - Flying hour program and actual experience captured in C-5HistDB	Number of TAI and PAA and total number of flying hours per year by aircraft type and component	1996-1998	Develop sortie length and mission cycle parameters
Reliability	G081/REMIS and C-5HistDB	Failure rates at the three-digit WUC level	1996-1998	Determines failure probability of subsystems
Maintainability	G081/REMIS and C-5HistDB	Maintenance man-hours per action at the three-digit WUC level	1996-1998	Determines downtime after adjustment to reflect mean time to repair
Type 6 Actions	G081/REMIS	Frequency of No Trouble Found actions	1996-1998	Adjusts reliability improvements to reflect various types of maintenance activities
Parallel/Sequential Repair Probability	AMC	The probability that a component in the failure group cannot be repaired while other repairs are taking place	NA	Adjusts binning (parallel repair) operations
Reliability Improvements	Lockheed Martin	Failure rate reductions as a result of modernization activities	Current through 2003	Determines the reliability levels of modernized C-5 aircraft
Equipment Criticality	MESL	Equipment criticality level	Current	Determines if failure of the component will result in an NMCR status

3. Sortie Duration and Mission Cycle Time

To run the simulation model, it is necessary to establish the mission sortie duration over which failures will be generated and the time between mission takeoffs, which we call Mission Cycle Time. We did not use distributions for these two parameters because it was felt that there would be negligible differences in results (for most common distributions) and the information gained was not worth the additional development effort and run time. We discuss here the peacetime calculations and show the adjustments for wartime in a later section.

To develop the average sortie duration for peacetime operation, we used total flying hours and total number of sorties from AMC-provided data for the years FY95 - FY98 for the C-5A and C-5B fleets. We also used data that reflected downtime of PAA aircraft as a result of scheduled maintenance.

Such scheduled maintenance includes home station checks, on-base refurbishments, and aircraft in a cannibalization status. Table 80 presents the basic flying hour and sortie data used for the peacetime sortie duration calculations.

Table 80. Flying Hour and Sortie Data for Use in Calculating Average Sortie Length

Aircraft	PAA	Total Flying Hours	Total Number of Sorties
C-5A			
FY95	66	21,613	6,344
FY96	66	28,713.	7,698
FY 97	66	24,009	6,657
FY 98	66	22,769.	5,982
C-5B			
FY95	44	25,805	6,736
FY96	44	37,677	9,021
FY 97	44	36,998	8,584
FY 98	44	41,331	8,936

Source: AMC

Dividing the total flying hours for each fleet over the 4-year data period by the total number of sorties during that period yielded an average peacetime sortie duration of 3.71 hours for the C-5A fleet and 4.37 hours for the C-5B fleet.

Another flying hour parameter needed for the simulation is the mission cycle time or the number of days between sortie takeoffs. During this period the aircraft flies a mission and, after landing, has preventative and corrective maintenance performed to get the aircraft ready for the next flight. To calculate the mission cycle time, expressed as Days Per Sortie, we used the following equations:

$$Days\ Per\ Sortie = \frac{365}{Number\ sorties\ per\ year\ per\ active\ PAA}$$

$$Number\ sorties\ per\ year\ per\ active\ PAA = \frac{Flying\ hours\ per\ year\ per\ active\ PAA}{Flying\ hours\ per\ sortie}$$

$$Flying\ hours\ per\ year\ per\ active\ PAA = \frac{Fleet\ Flying\ hours\ per\ year}{Number\ active\ PAA}.$$

$$Number\ active\ PAA = Total\ PAA \times (1 - \Pr(SM\ or\ Cann)) \quad . \tag{II-4}$$

We used the number of active PAA rather than total PAA because, at any one time, one or more aircraft are likely to be in a non-flying status because of scheduled maintenance (such as a home station check) or because an aircraft is in a cannibalization status (cann bird). Thus, scheduled maintenance (other than between sorties) does not allow for a continual operation and increases the flying hour burden on the other aircraft. As a simple example, if there are 10 aircraft and one is designated as a "cann bird," then the flying hour responsibilities fall to the remaining nine and thus they must fly more sorties. Our data indicated that an aircraft's probability of being in scheduled maintenance or in a cann-bird status was approximately 0.13 for the C-5A and approximately 0.10 for the C-5B. Using the available flying hour data and the above equations, we found that for the C-5A, the average cycle time was 3.1 days, and it was 1.6 days for the C-5B. Note that the longer cycle time for the C-5A is not because it has a higher rate on non-availability, which it does, but because the flying hour requirement is much less severe than for the C-5B.

4. Calculation of Current MCR Rates and Calibration Targets

We used average MCR data from 1996-1998 as our calibration standard. These data showed that the C-5A had an NMCR of 42.3 percent, while the C-5B had an NMCR of 31.6 percent over this time period. Before using these data, we adjusted it to account for factors not included in our model.

The simulation only calculates downtime caused by subsystem failure and repair. Other factors contribute to not mission capable time, however, in particular scheduled maintenance and cannibalization. When an aircraft has been cannibalized for parts, it is counted as non-mission capable. Our model assumes, however, that an aircraft will be repaired and returned to flight status when repairs are completed, which is not true of a cannibalized aircraft. Similarly, an aircraft that is undergoing isochronal inspections, home station checks, or refurbishment counts as non-mission capable, even if no subsystems have failed.

USAF data show that C-5A aircraft had NMCR time of 4.5 percent for isochronal inspections, 0.3 percent for home station checks, 0.9 percent for refurbishment, 5.2 percent for cannibalization, and 2.1 percent for other, non-identified causes. Subtraction of these sources of NMCR produces a calibration target of 29.3 percent NMCR.

C-5B aircraft have an NMCR of 2.6 percent for isochronal inspections, 1.3 percent for home station checks, 1.9 percent for refurbishment, 3.8 percent for cannibalization, and 1.7 percent for other causes. Subtraction of these sources of NCMR produced a calibration target of 20.3 percent for the C-5B.

5. The Effect of Letter Check on MCR

Letter check is a concept borrowed by the commercial airlines to define an annual maintenance policy in which programmed depot maintenance, refurbishments, and isochronal inspections are replaced by an annual maintenance process. Letters of the alphabet, starting with A, identify the scope of the policy. In this case, the applicable letter is "C" and in some references the term C-Check has been used. Currently, C-5 aircraft are programmed into depot maintenance every 5-7 years for major structural inspections and overhauls, and isochronal maintenance is scheduled approximately every 400 hours. Major modifications or refurbishments are often done during PDM. If the letter check coincides with a home station check, then the two might be done together. Lockheed has proposed that the letter check be defined over a 7-year cycle.

The Air Force has indicated that aircraft undergoing letter check will not be considered possessed, presumably because it is a form of depot maintenance. This is important with respect to how mission capable rate is measured. Consider the following three kinds of scheduled maintenance activities: PDM, isochronal inspections, and refurbishments. These three activities, which are currently scheduled at different intervals, are to be replaced by a letter check activity, which is scheduled annually. PDM time is non-possessed time and thus does not contribute to NMCR; but that is not true for isochronal inspections or some refurbishments. By going to letter check, which absorbs the isochronal and refurbishment activity, there is a "MCR bookkeeping" benefit since the downtime of these two activities no longer counts against the MCR rate. The effect of going to letter check on MCR is shown in Table 81.

Table 81. Contributions to NMCR of Isochronal Inspections and Refurbishments.

Activity	Current NMCR	
	C-5A	C-5B
Isochronal Inspection	4.5%	2.6%
Refurbishment	0.9%	1.9%
Total	5.4%	4.5%

We have seen that isochronal inspection accounts for an NMC rate of 4.5 percentage points of NMC for the C-5A aircraft and 2.6 percent for the C-5B. For refurbishment, the NMC rate is 0.9 percent for the C-5A and 1.9 percent for the C-5B. Adding the NMC rates together, the potential benefit to MCR of letter check is 5.4 percent for the C-5A and 4.5 percent for the C-5B. These improvements are significant but should be recognized that they are partially a result of how MCR is defined and measured. If the time to perform a letter check was considered to be possessed time, then the MCR rate would actually go down as a result of this maintenance policy. Aircraft availability should also be considered in evaluating letter check's impact on aircraft effectiveness. One way is to estimate the percentage of total fleet availability before and after letter check, without regard to the notion of possessed time. Thus, letter check would be considered a benefit to fleet effectiveness if the total time for the maintenance activities it combines is less than it was before letter check. IDA did not perform such an analysis.

6. AMP Items

In 1998 the U.S. Air Force awarded Lockheed Martin a contract to upgrade the C-5 avionics, the Avionics Modernization Program (AMP). The AMP includes removal of a variety of components and the addition of modernized replacements. We modeled this upgrade by accounting for both the added and removed components at the three-digit WUC level. Lockheed Martin provided mean time between failures (MTBF) data for 57 items that were to be removed from the aircraft during the upgrade. These items were accounted for in the data at the five-digit WUC level. Lockheed also provided data for 49 items to be added as part of the upgrade. Again, accounting was done at the five-digit level. Separate data for C-5A and C-5B were not provided, so we assumed that the failure rates on both new and removed components were the same for both model aircraft.

To use these data, we had to convert the MTBF values to events per 1,000 hours as used in the simulation model, and we had to aggregate the five-digit data to the three-digit level. For every component that is removed from the aircraft, it was necessary to also remove its associated failures from the baseline model, and the various scenarios we modeled required tracking both the modernized and unmodernized configuration. This accounting required consistent data aggregation.

For example, Lockheed showed that AMP would remove two of the items in the 14C WUC group, the upper rudder position transducer (14CGC) and the lower rudder position transducer (14CGD). We simply summed the reciprocal of the MTBF values, and took the reciprocal of this value to get the change in failures per 1,000 flight hours due to the removal of these items.

$$\Delta events / 1000hr(14C) = \frac{1}{\dfrac{1}{MTBF(14CGC)} + \dfrac{1}{MTBF(14CGD)}}. \qquad \text{(II-5)}$$

Similarly, we aggregated the data for the components that we added for the AMP upgrade, creating a list of 21 three-digit items from the original list of 49 five-digit items supplied by Lockheed. The failure rates for these items were added to the simulation for iterations that included the AMP upgrade.

7. Other Modernized Components

Data for non-avionics components were provided in a different form than the avionics upgrade components and required different manipulation for use in the simulation model. Lockheed-Martin's modernization proposal included improvements to 32 three-digit WUC non-avionics components. These components were assumed to be modernized in alternatives that were labeled "Partial Upgrade" and "Full Upgrade" in this study. The "Baseline" and "FY04" configurations assume that these components are not modernized.

We used data from G081 to determine failure rates for these components in the baseline configuration. For the modernized alternatives, we made improvements to these failure rates based on data from Lockheed. Lockheed determined these improvements from historical failure data, failure modes, and analysis of the modernized configurations. Their results were presented as a percentage by which events per 1,000 hours would be improved with modernization. For improvements to a fuel access door, for example, Lockheed estimated that the new design would improve the 6.7 events per 1,000 flight hours by 80 percent to 1.3 events per 1,000 hours. We multiplied the baseline failure rate from the G081 data by the complement of Lockheed's improvement percentages to calculate the modernized failure rate. C-5A and C-5B failure rates and improvements were calculated and tracked separately.

D. CHANGES IN WARTIME

In a wartime environment, experience as well as reasoning indicates that mission capable rate will increase. In such an environment, there is much greater urgency to keep an aircraft operational and, to do so, people generally work longer and harder. That in itself is an important component to increased MCR. But there are other factors. More maintenance and logistics people may be assigned, reserve spares pools are employed, and aircraft may be flown in a marginal condition, which in peacetime would be considered NMC. For our wartime analysis, we considered two periods: the Surge period, a 45 day span following the outbreak of the conflict; and a Sustain period, which follows the Surge period.

To account for the overall effect of the wartime environment, we used data from the Desert Shield/ Desert Storm experience for the C-5A and C-5B. These data were available at AMC. By comparing the MCR rates before and during each of the two surge/sustain periods, we determined that the not-mission-capable time was reduced by about 20 percent for the C-5A and 24 percent for the C-5B. These adjustments were then applied to the current peacetime C-5 NMC rates used. Thus the current baseline peacetime NMC value reduced from 42.3 - 33.7 percent for the C-5A (0.80 x 42.3) and from 31.6 - 24.1 percent for the C-5B (0.76 x 31.6). Rounding accounts for any slight variations.

Given the current baseline Surge and Sustain overall MC rates, we then estimated the effects of wartime policy decisions on MCR through deferring scheduled maintenance activities. After accounting for such deferrals, we can then calculate the baseline NMC rate due to failures or corrective maintenance, which will then allow us to evaluate the proposed reliability improvements.

1. Non-Failure NMC Changes

Adjustments to the non-failure contributors to NMCR for the Surge and Sustain periods were as follows:

- **Isochronal Inspections**—We assumed such inspections would be deferred in the Surge period only, and thus the NMCR of 4.5 percent for the C-5A and 2.6 percent for the C-5B were reduced to zero. Recall that, under letter check, there are no isochronals so that the savings indicated only apply to the baseline configuration without letter check.
- **Refurbishments**—We assumed refurbishments would be deferred in the Surge and Sustain periods and thus the NMCR of 0.9 percent for the C-5A and 1.9 percent for the C-5B were reduced to zero. These reductions only apply to the baseline configuration without letter check since refurbishments are included within the letter check process.
- **Home Station Checks**—We assumed home station checks would be deferred in the Surge period only and thus the NMCR of 0.3 percent for the C-5A and 1.3 percent for the C-5B were reduced to zero. These reductions apply to all configurations.
- **Other**—We assumed actions related to other causes of NMC time would be deferred in the Surge period only and thus the NMCR of 2.1 percent for the C-5A and 1.7 percent for the C-5B were reduced to zero. These reductions only apply to all configurations.
- **Cannibalization**—We assumed that during Surge and Sustain, cann birds would still be needed so that there is no reduction in NMC time.

2. Flying Hour Program

Another major change in wartime is the flying hour program. For operation in either Surge or Sustain, we assumed that the nominal value for each sortie lasted 6 hours and that the aircraft operated for 10 hours per day. These values apply to both the C-5A and C-5B. This results in a mission cycle time of 14 hours or about 0.6 days. To provide some variability, we assigned a 75 percent weight to the 6-hour value, and a weight to 25 percent to a 6.5-hour sortie duration.

3. C-5A vs. C-5B Repair Times

Another significant change for Surge and Sustain operations was to assume that the repair times for the C-5A and C-5B aircraft would be the same. Historical data show this is not the case, with C-5A repair times generally longer than those of the C-5B. This could be due to differences in parts or designs, or, more likely, differences in the maintenance environment. The C-5A fleet is split between the active fleet and Guard/Reserve, in a ratio of about 1 to 2, while all of the newer C-5Bs are in the active fleet. We assumed that the maintenance environment is the primary cause of differences between the A and B fleet repair times and that after upgrade the two fleets will be closer in configuration. This led to the decision to make the C-5A and C-5B repair times the same during the Surge and Sustain periods.

4. Binning

Recall that for peacetime operation we used three repair lines or bins with probabilities of 60, 30 and 10 percent. For wartime operation, we assumed that with the greater manpower pool available and the urgency to get aircraft operationally ready, that two bins would be applicable with probabilities of 95 and 5 percent. Thus, the likelihood that most repairs would take place simultaneously increases significantly in wartime. Note, however, that we have defined certain subsystems that must be repaired sequentially for either safety or accessibility reasons. These subsystems are not subject to binning.

E. RESULTS

Table 82 summarizes the results of the simulation runs after all data were collected and prepared in the manner described above.

Table 82. Summary of Mission Capable Rate Results

Configuration	Aircraft	Mission Capable Rate Peacetime	Surge	Sustain
Current w/o Letter Check	C-5A	57.7 %	66.7%	58.9%
	C-5B	68.4%	75.9%	68.4%
	Fleet	62.0%	70.4%	62.7%
Current w/ Letter Check	C-5A	63.1%	66.7%	64.3%
	C-5B	72.9%	75.9%	72.9%
	Fleet	67.0%	70.4%	67.8%
FY04 Baseline w/o Letter Check	C-5A	57.8%	66.8%	59.9%
	C-5B	68.7%	76.1%	70.5%
	Fleet	62.2%	70.5%	64.1%
FY04 Baseline w/ Letter Check	C-5A	63.2%	66.8%	64.4%
	C-5B	73.2%	76.0%	73.0%
	Fleet	67.2%	70.5%	67.9%
Partial Upgrade w/ Letter Check	C-5A	65.2%	70.7%	68.3%
	C-5B	74.9%	77.8%	74.8%
	Fleet	69.1%	73.5%	70.9%
Full Upgrade w/ Letter Check	C-5A	66.7%	73.0%	70.6%
	C-5B	76.4%	79.5%	76.5%
	Fleet	70.6%	75.6%	73.0%

For peacetime operation, the current C-5 fleet has a MCR of 62 percent; 57.5 percent for the C-5A fleet and 68.4 percent for the C-5B fleet. After improvements are implemented over the FY 1999 to FY 2003 timeframe, the corresponding fleet MCR improves from 62.0 - 62.2 percent, not very significant. It is our contention that too much masking is taking place to allow for significant improvements. Thus, while the AMP modification does significantly improve the avionics reliability of the aircraft, reducing avionics failure rate is allowing other components to enter the "visible NMC" domain. However, when letter check is introduced, we see a more significant improvement in NMC, primarily because of the way NMC is measured. Going from the FY04 baseline with letter check to Partial Upgrade to Full Upgrade, the C-5 fleet mission capable rate increases from 67.2 percent to 69.1 percent to 70.6 percent.

For the wartime scenarios, Surge and Sustain, we see a similar progression of NMC as for peacetime operation. Even though the aircraft operate much more, the way we handled the non-corrective maintenance portions of NMC and the assumptions made about the wartime maintenance environment results in a decidedly better MCR picture.

For example, for the FY04 Baseline with letter check, the peacetime fleet MCR was 67.2 percent; it is 70.5 percent for the Surge case and 67.9 percent for Sustain. For the Full Upgrade case, the three comparable MCR values, Peacetime, Surge, Sustain, are 70.6 percent, 75.6 percent, and 73.0 percent, respectively.

Table 83 shows the breakdown of Not Mission Capable Rate by failure causes, scheduled maintenance events, and cannibalization. From this table, one can see how, for example, letter check removes a significant portion of the NMC total due to the removal of scheduled maintenance NMC time (i.e., isochronal inspections) and how Peacetime, Surge, and Sustain NMC differences occur. For example, we see for the C-5A that isochronal inspections contribute 4.5 percent to NMCR in peacetime for the FY04 Baseline Configuration without letter check. When letter check is introduced for the same aircraft configuration, that 4.5 percent NMCR is eliminated. For home station check, we see that its contribution to NMCR for the C-5B (1.3 percent) is eliminated for Surge, but it is reintroduced for the Sustain period.

Table 83. Not Mission Capable Contribution for Various Causes for All Configurations and Operational Scenarios.

Config-uration	A/C Type	NMCR Contribution of Failures (%)		NMCR Contribution of Isochronal Inspection (%)			NMCR Contribution of Refurbishnment (%)			NMCR Contribution of Cannibalization (%)			NMCR Contribution of Home Station Check (%)			NMCR Contribution of Other Maintenance (%)			Total Not-Mission Capable Rates (%)		
		Peace	Surge/ Sust.	Peace	Surge	Sust.	Peace	Surge	Sust.	Peace	Surge	Sust.	Peace	Surge	Sust.	Peace	Surge	Sust.	Peace	Surge	Sust
Current w/o Letter Check	C-5A	29.3	28.1	4.50	0.0	4.5	0.90	0.0	0.9	5.2	5.2	5.2	0.3	0.0	0.3	2.1	0.0	2.1	42.3	33.3	41.1
	C-5B	20.3	20.3	2.60	0.0	2.6	1.9	0.0	1.9	3.8	3.8	3.8	1.3	0.0	1.3	1.7	0.0	1.7	31.6	24.1	31.6
Current w/ Letter Check	C-5A	29.3	28.1	0.0	0.0	0.0	0.0	0.0	0.0	5.2	5.2	5.2	0.3	0.0	0.3	2.1	0.0	2.1	36.9	33.3	35.7
	C-5B	20.3	20.3	0.0	0.0	0.0	0.0	0.0	0.0	3.8	3.8	3.8	1.3	0.0	1.3	1.7	0.0	1.7	27.1	24.1	27.1
FY04 Baseline w/o letter check	C-5A	29.2	28.0	4.50	0.0	4.5	0.9	0.0	0.0	5.2	5.2	5.2	0.3	0.0	0.3	2.1	0.0	2.1	42.2	33.2	40.1
	C-5B	20.0	20.2	2.60	0.0	2.6	1.9	0.0	0.0	3.8	3.8	3.8	1.3	0.0	1.3	1.7	0.0	1.7	31.3	24.0	29.6
FY04 Baseline w/ letter check	C-5A	29.2	28.0	0.0	0.0	0.0	0.0	0.0	0.0	5.2	5.2	5.2	0.3	0.0	0.3	2.1	0.0	2.1	36.8	33.2	35.6
	C-5B	20.0	20.2	0.0	0.0	0.0	0.0	0.0	0.0	3.8	3.8	3.8	1.3	0.0	1.3	1.7	0.0	1.7	26.8	24.0	27.0
Partial Upgrade w/ Letter Check	C-5A	27.2	24.1	0.0	0.0	0.0	0.0	0.0	0.0	5.2	5.2	5.2	0.3	0.0	0.3	2.1	0.0	2.1	34.8	29.3	31.7
	C-5B	18.3	18.4	0.0	0.0	0.0	0.0	0.0	0.0	3.8	3.8	3.8	1.3	0.0	1.3	1.7	0.0	1.7	25.1	22.2	25.2
Full Upgrade w/ Letter Check	C-5A	25.7	21.8	0.0	0.0	0.0	0.0	0.0	0.0	5.2	5.2	5.2	0.3	0.0	0.3	2.1	0.0	2.1	33.3	27.0	29.4
	C-5B	16.8	16.7	0.0	0.0	0.0	0.0	0.0	0.0	3.8	3.8	3.8	1.3	0.0	1.3	1.7	0.0	1.7	23.6	20.5	23.5

For any aircraft fleet, one cause of downtime is not having parts available to restore failed subsystems to a mission capable state. As stated earlier, this problem is of such a concern to the C-5 community that aircraft are designated to be cann birds to act as an immediate supply source. The Air Force has determined that such a policy improves overall MCR even though the cann bird is, itself, NMC. AMC asked us to evaluate the potential improvement in MCR if, as a result of developing a modernized C-5, the supply support resources were increased to full funding.

A rough-order-of-magnitude (ROM) analysis was performed. The approach was as follows:

- Determine the Not Mission Capable Supply (NMCS) standards for Active, Guard, and Reserve fleets.
- Determine the current NMCS levels for Active, Guard, and Reserve fleets.
- Assume that if the current NMCS value is greater than the corresponding standard value, then full supply support funding under the Full Upgrade configuration will reduce NMCS to the standard value. The values to be changed are the cannibalization NMC values.
- Assume that for the Partial Upgrade configuration, the supply funding is proportional to the reliability reduction compared to the Full Upgrade and thus the reduction in NMCS is proportional to the relative reliability improvement.

Based on above analysis, the old and new cannibalization NMC rates are as shown in the Table 84. It is seen that the current C-5A cannibalization NMCR of 5.2 percent could reduce to 2.0 percent under full supply support funding with the Full Upgrade configuration. The Partial Upgrade cann NMCR is 3.5 percent with less than full funding and a lower reliability level. Similarly, for the C-5B, the cann NMCR goes from the current 3.8 - 2.6 percent for the Partial Upgrade to 1.8 percent for the Full Upgrade.

A more complete analysis would require that we get a more complete understanding of the NMCS Standard definition and values, determine what the current funding posture is, determine how it might change in the future, and determine whether we have to treat changes in funding between the Active, Guard, and Reserve fleets differently.

Table 84. ROM Estimates of the Effect of Increased Supply Support Funding on Cannibalization NMCR

Aircraft	Current Cann NMCR	Cann NMCR With Increased Supply Support Funding	
		Partial Upgrade	Full Upgrade
C-5A	5.2%	3.5%	2.0%
C-5B	3.8%	2.6%	1.5%
Fleet	4.6%	3.1%	1.8%

F. VERIFICATION & VALIDATION OF THE MCR MODEL

We conducted a verification and validation process of the MCR model to determine whether the developed model is suitable for predicting the C-5 NMCR.

The verification and validation of the model was performed by a series of executions of the MCR model using different parameter values. Because there are a huge number of combinations of parameters and corresponding values, the testing was not exhaustive. Nonetheless, the parameters and their values were selected so that they represent a large portion of the model parameter space. The intent of this testing was to determine whether reasonable and consistent outputs were produced across the parameter space of the model by exercising the model through a range of realistic input parameters. The following sections will examine the main parameters of the model and analyze its impact on model results.

Any assumption of the model will influence the fidelity of the results to some degree. Therefore, the implicit and explicit assumptions of the model, as well as any implied constraints that are a consequence of these assumptions were also examined as part of the verification and validation process.

1. Effect of Number of Monte Carlo Trials

The MCR model is stochastic in nature to capture the complex effects of failure masking and component failure and repair.

The MCR calculation process that was explained in previous sections is repeated for multiple missions. Each Monte Carlo iteration requires three random draws. The probability that a given part fails on the particular flight is calculated by assuming an exponential distribution. The first random draw is compared to this probability to determine whether the part has failed. The second random draw is taken against a log-normal distribution to determine the repair time of the failed part. The log-normal distribution has a mean based on the average downtime of the part. The source of the average downtime is the G081 for items not to be modernized and from Lockheed Martin for parts to be modernized. The coefficient of variation of the distribution is assumed to be 0.3. The final random draw is used to determine the repair bin of the failed part. The average NMCR is computed using these Monte Carlo trials.

For such Monte Carlo simulation as the MCR model, there is a tradeoff between the accuracy of the simulation and the required computational time. Therefore, the effect of the number of Monte Carlo trials on the MCR model results was investigated to determine the number of trials required for an accurate simulation. Figure 31 shows the results of this assessment.

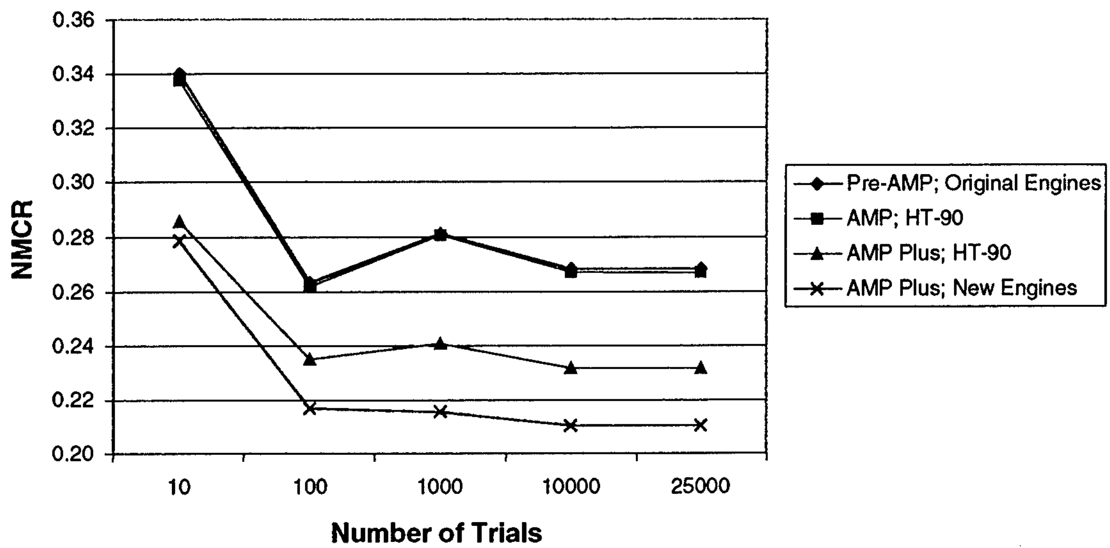


Figure 31. Effect of Monte Carlo Trials on MCR Model Results

For all four C-5 modernization options, the NMCR value fluctuates significantly during the early part of simulation. The model results then stabilize and do not vary after 10,000 iterations. Therefore, 10,000 Monte Carlo trials were used as the number of trials required for subsequent calculations.

2. Effect of Mean Downtime Calibration Factor

The initial results of the MCR model are calibrated to the average C-5 MCR values from 1996-98. For the calibration, the mean downtime is the parameter that is factored to calibrate MCR model results to historical values. The ratio of the actual historical NMCR against the estimated NMCR results of the model is used as the calibration factor.

When more than one item fails, the required repair time is determined by the part with the longest repair time, i.e., the pacing item. When repair time for the pacing item is improved by either reducing failure rate or mean downtime, the next pacing item is unmasked by the improvement, and its downtime determines the NMCR.

The magnitude of the calibration factor that is used to adjust the mean downtime to match historical values is identical for all parts, regardless of its failure rate and downtime. For these reasons, the impact of the calibration factor should be linear as shown in Figure 32.

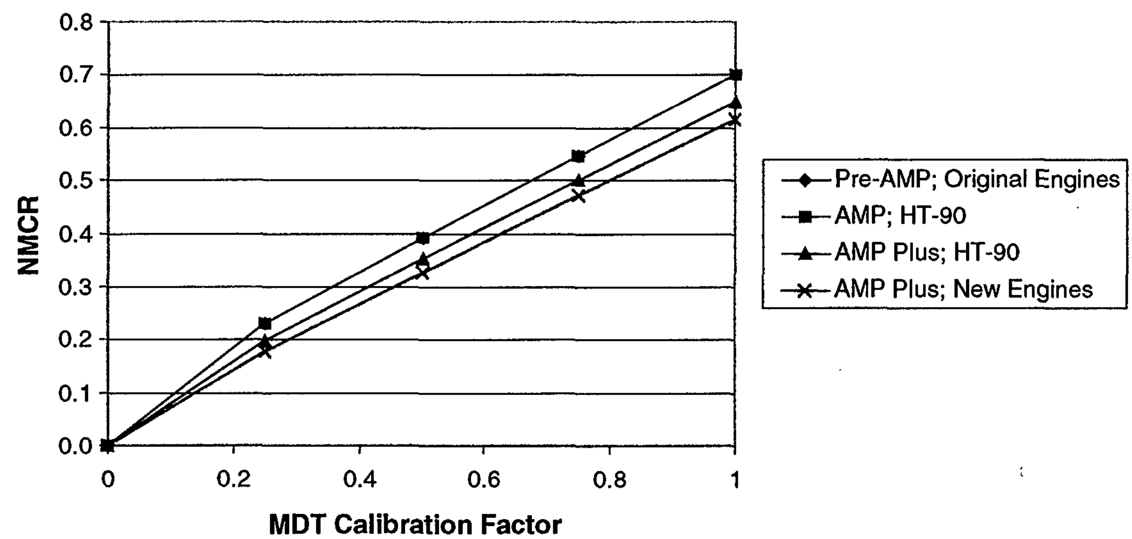


Figure 32. Effect of Mean Downtime Calibration Factor

3. Effect of Mean Downtime Coefficient of Variation

When determining the downtime for a failed part, a random draw is taken against a lognormal distribution with a mean based on the average downtime of the part. The average downtime is based on data from G081 for items not to be modernized and from Lockheed Martin for parts to be modernized. The coefficient of variation of the distribution is assumed to be 0.3. To study the sensitivity of the MCR model results to this parameter, the coefficient of variation was varied from 0.1 to 0.9 in 0.2 intervals. The resulting NMCR is illustrated in Figure 33, in which the model is calibrated for the 0.3 MDT coefficient of variation. Due to the unsymmetrical biased nature of the lognormal distribution toward larger values, as expected, the NMCR increases with the coefficient of variation. However, changes to the coefficient of variation effect all options equally, as demonstrated by the nearly parallel lines in the graph. Therefore, it would take drastic changes in the selected coefficient to make an appreciable change in the analysis results. This is because the baseline configuration is calibrated to historical data, while all other options are calculated as changes from this baseline.

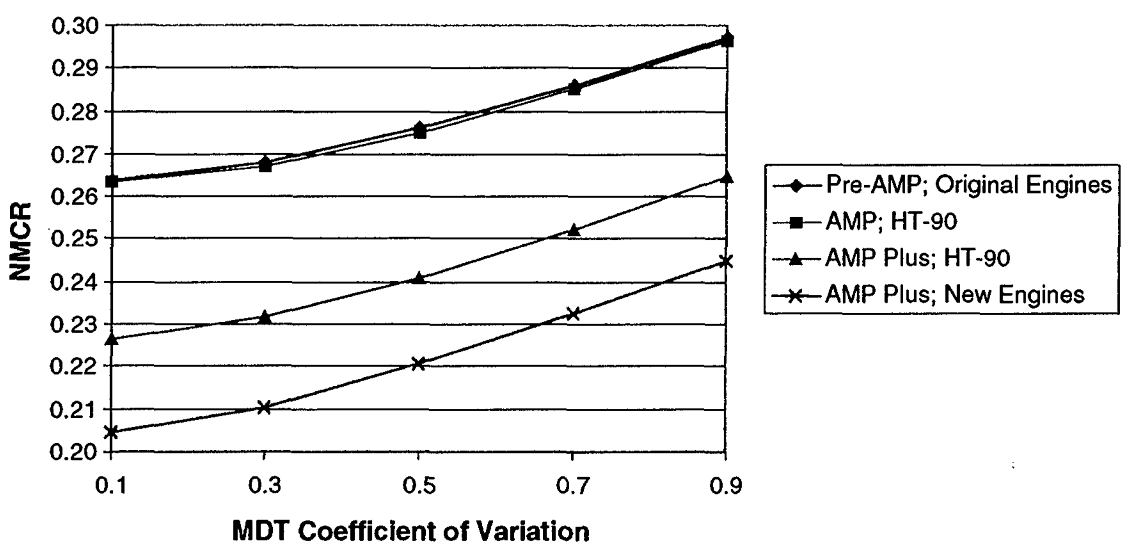
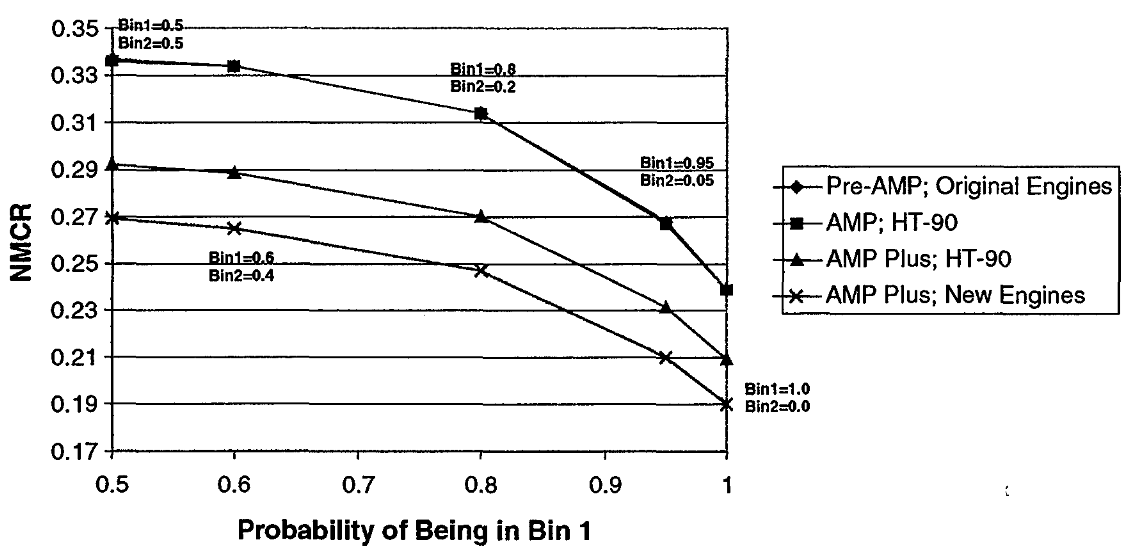


Figure 33. Effect of Mean Downtime Coefficient of Variation

4. Effect of Repair Bin Probability

When multiple failures occur, manpower and facility constraints dictate that some repairs will be done serially in separate repair bins rather than in parallel. The model assumes that during peacetime, three bins are used where 60 percent of the failures are repaired in bin 1, 30 percent in bin 2, and 10 percent in bin 3. During surge situations, the MCR model uses two repair bins with a probability of 90 percent and 10 percent. The bin where a failed part is repaired is determined by a random draw for each Monte Carlo iteration.

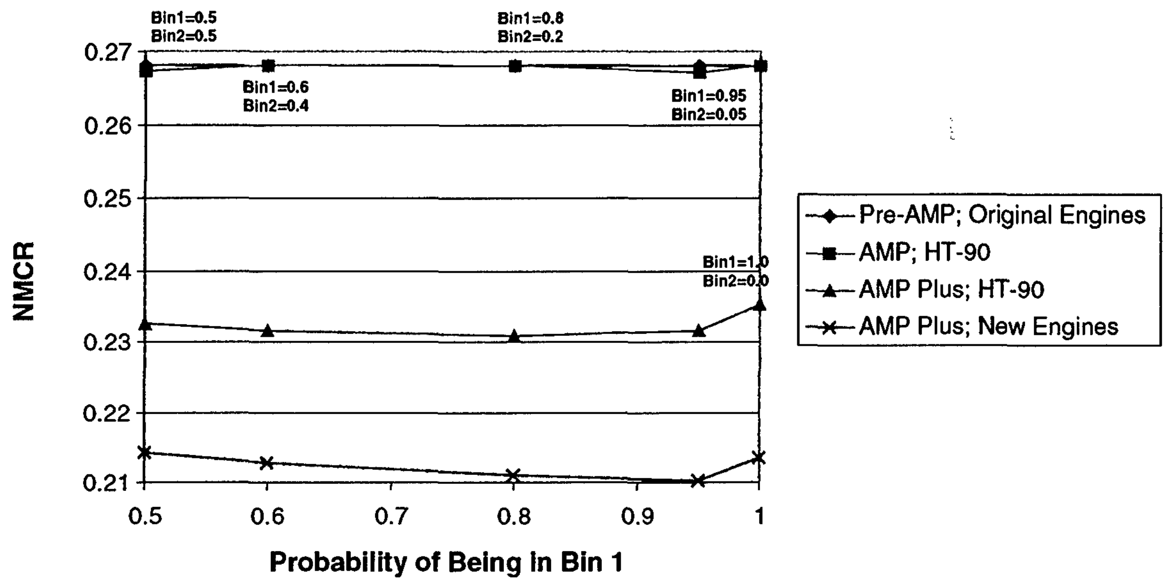
Changing the bin 1 probability to 100 percent gives the most conservative answer for what impact a given part repair will have. It is equivalent to assuming that when the plane lands, unlimited manpower and physical space is available so that every part that requires repair can be fixed simultaneously. As the bin 1 probability is reduced, the number of serial repairs increase. For these reasons, as show in Figure 34, the NMCR will reduce as the bin 1 probability increases.



(Model calibrated to the 0.95 bin 1 probability case)

Figure 34. Effect of Repair Bin Probability on MCR Model Results

The previous results shown in Figure 31 represent the case where the model was calibrated to the default 0.95 bin 1 probability case. If the model is calibrated for the Pre-AMP, original engine case for each separate bin 1 probability, Figure 35 illustrates that there is little change in the model NMCR results. This indicates that as long as the model is calibrated to historical data, the relative impact of modernization to the C-5 NMCR is insensitive to the bin probabilities and therefore this parameter is not a major driver of the model results.



(Model calibrated separately for each bin1 probability case)

Figure 35. Effect of Repair Bin Probability on MCR Model Results

5. Effect of Type 6 Repair Rates

The G081 data base lists the type and number of failures for each part of the C-5. The failures are categorized into six types. A Type 6 failure is a case where the pilot suspects a failure or the diagnostic electronics indicate that a part needs repair. Discussions with USAF personnel indicated that the Type 6 repair rate may be overstated. The rate that an actual repair is performed for such cases is defined as the Type 6 repair rate and its default value is set at 0.5. As expected, Figures 36 and 37 illustrate that as the Type 6 repair weight increases, the number of failures and NMCR also increase in a linear fashion.

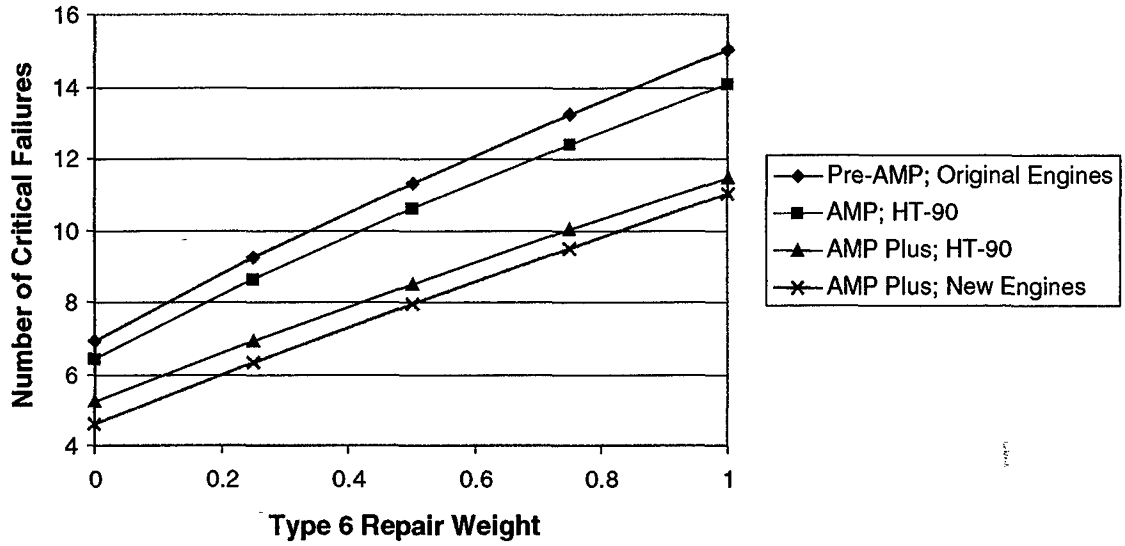
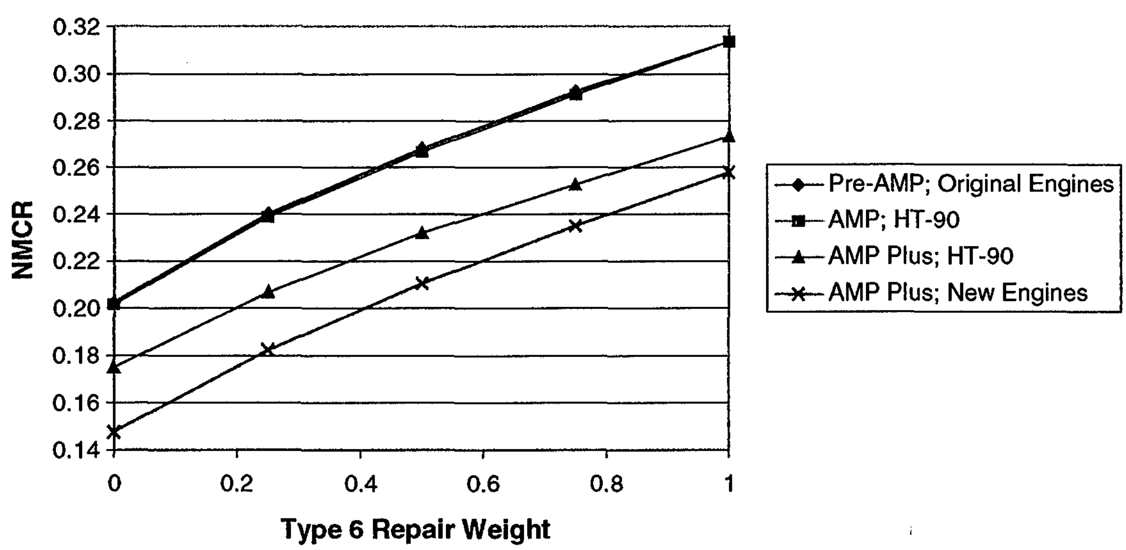


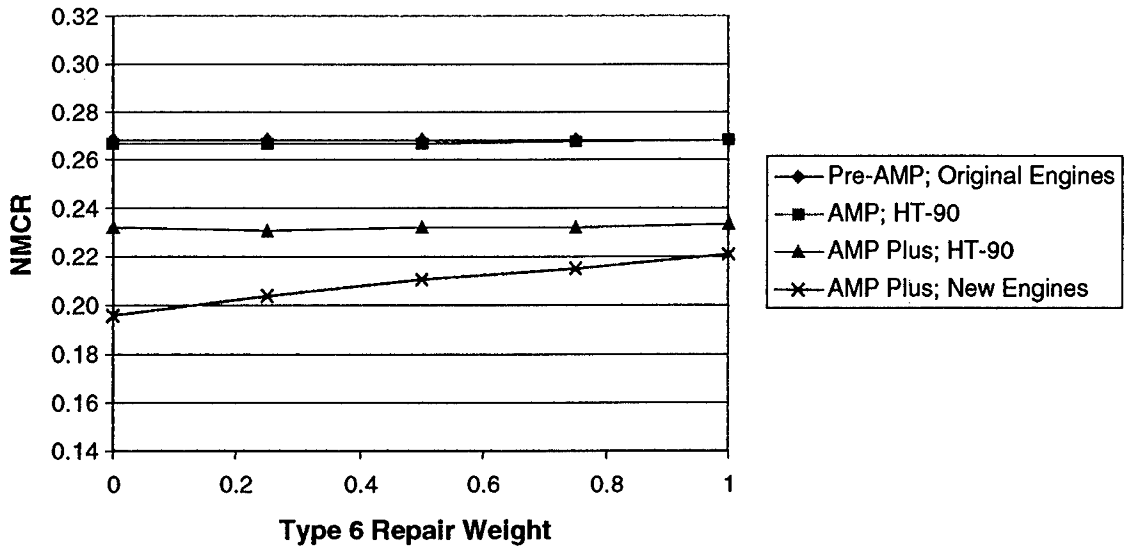
Figure 36. Effect of Type 6 Repair Weight on Number of Critical Failures



(Model calibrated to the 50 percent repair weight case)

Figure 37. Effect of Type 6 Repair Weight on MCR Model Results

The previous results shown in Figure 37 represent the case where the model was calibrated to the default 50-percent Type 6 repair weight case. If the model is calibrated for the Pre-AMP, original engine case for each separate repair weight, Figure 38 illustrates that there is little change in the results of the MCR model. This indicates that as long as the model is calibrated to historical data, the relative impact of modernization to the C-5 NMCR is insensitive to the Type 6 repair weight and, therefore, this parameter is not a major driver of the model results.



(Model calibrated to each Type 6 repair weight case)

Figure 38. Effect of Type 6 Repair Weight on MCR Model Results

6. Comparison of MCR Model Results with Historical Data on C-5 Departure Delays

As with other models of this type, validation efforts based on comparison with test data cannot address the performance of the model throughout its full range of capability. Nonetheless, such individual comparisons do provide a data point against which model outputs with specific set of input conditions can be compared.

Because this model is calibrated to historical MCR rates, a comparison between the model rates and previous C-5 MCR rates is meaningless. Nonetheless, the MCR model results were compared with historical data of C-5 departure delays due to maintenance. The contribution of the major components to MCR and departure delay are compared and shown in Figures 39 and 40. The components are compared for the number of incidents and maintenance hours.

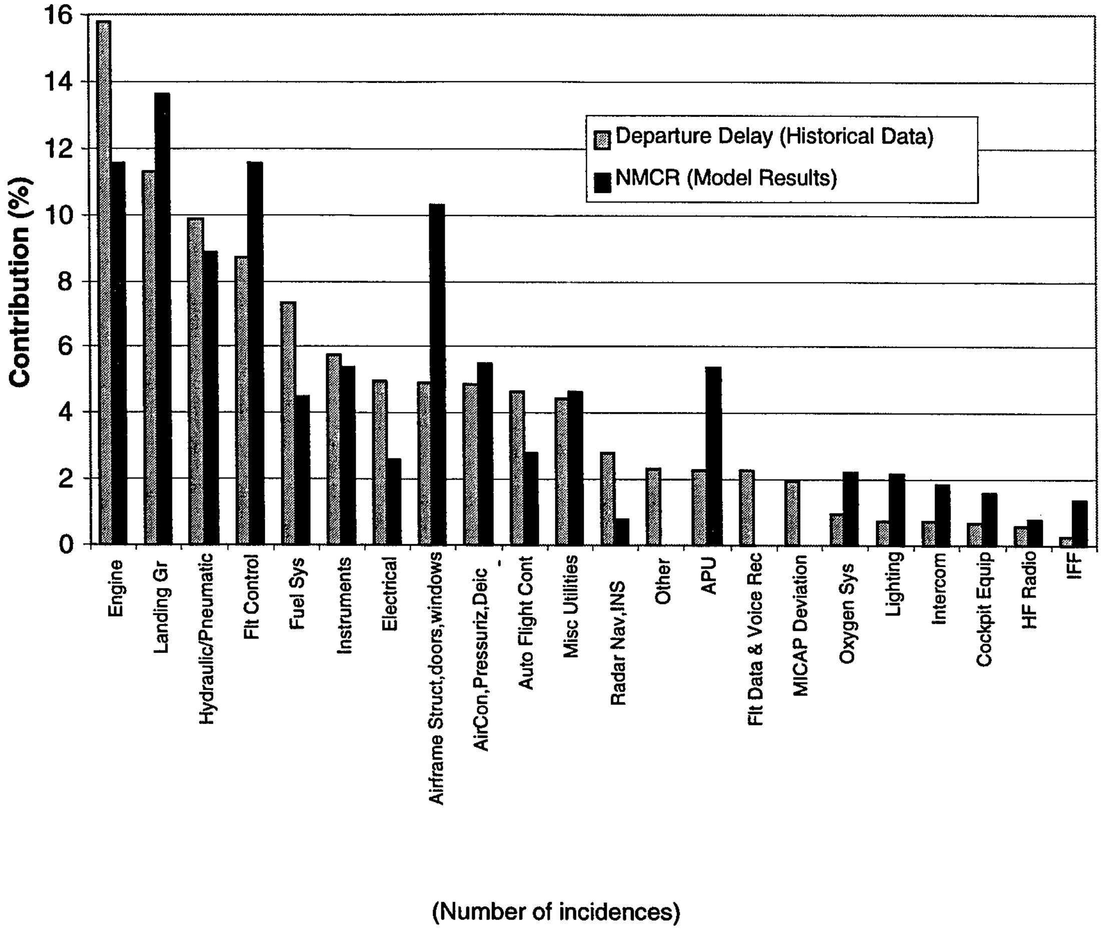


Figure 39. Comparison Between Historical Data on C-5 Departure Delay due to Maintenance and MCR Model Results

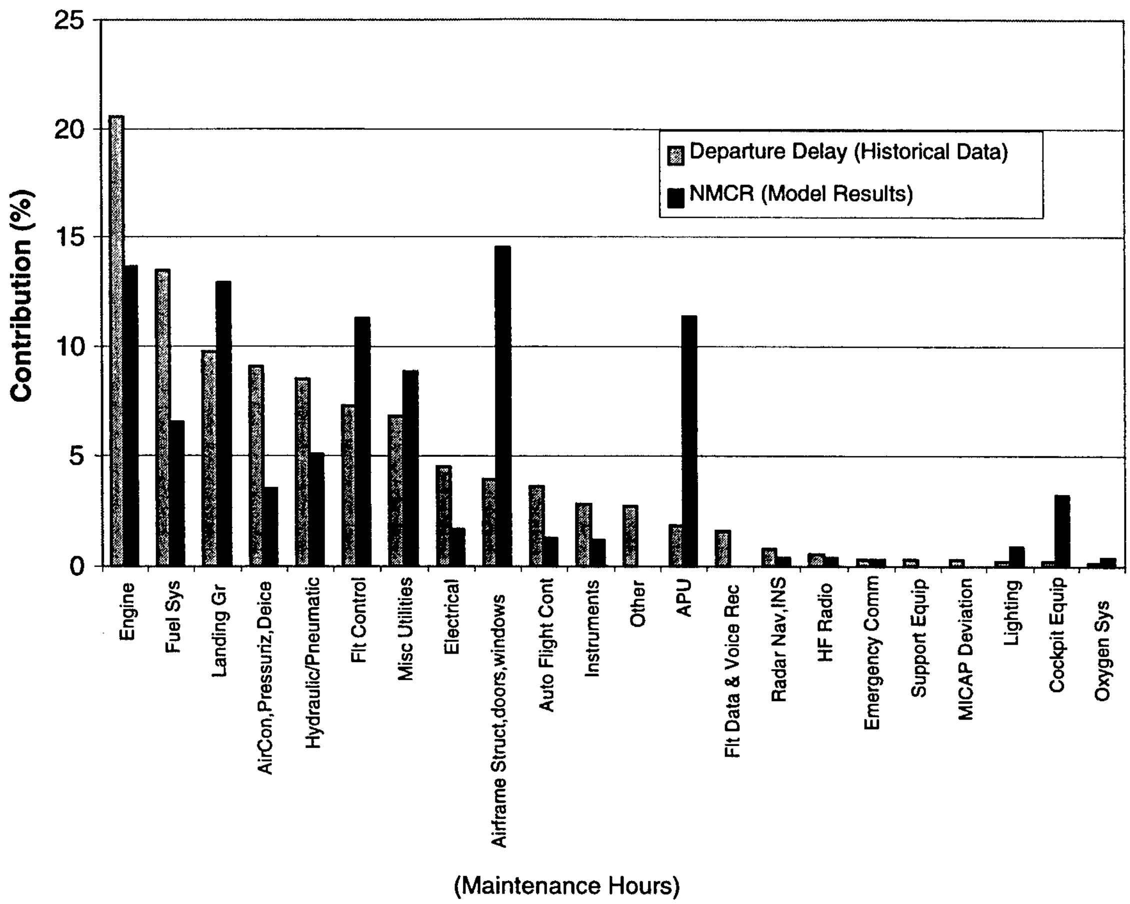


Figure 40. Comparison Between Historical Data on C-5 Departure Delay due to Maintenance and MCR Model Results

Although many other elements, such as runway infrastructure, will influence departure delay and not MCR and there is no simple direct relationship between departure delay and MCR, the components that influence departure delay due to maintenance and their corresponding contribution to MCR should be related and somewhat comparable.

The results of Figures 39 and 40 indeed indicate that the magnitude of contribution of components that contribute to departure delay compare fairly with their contribution to NMCR.

7. Additional Modernization Items to Improve MCR

The MCR model was used to determine potential items of the C-5 that could be modernized to reduce the NMCR. The parts considered for analysis were those that were not modernized for the AMP plus, new engine case. Cost of modernization was not considered when determining potential modernization required parts.

The top 10 items that were identified are shown in Figure 41 and listed in Table 85.

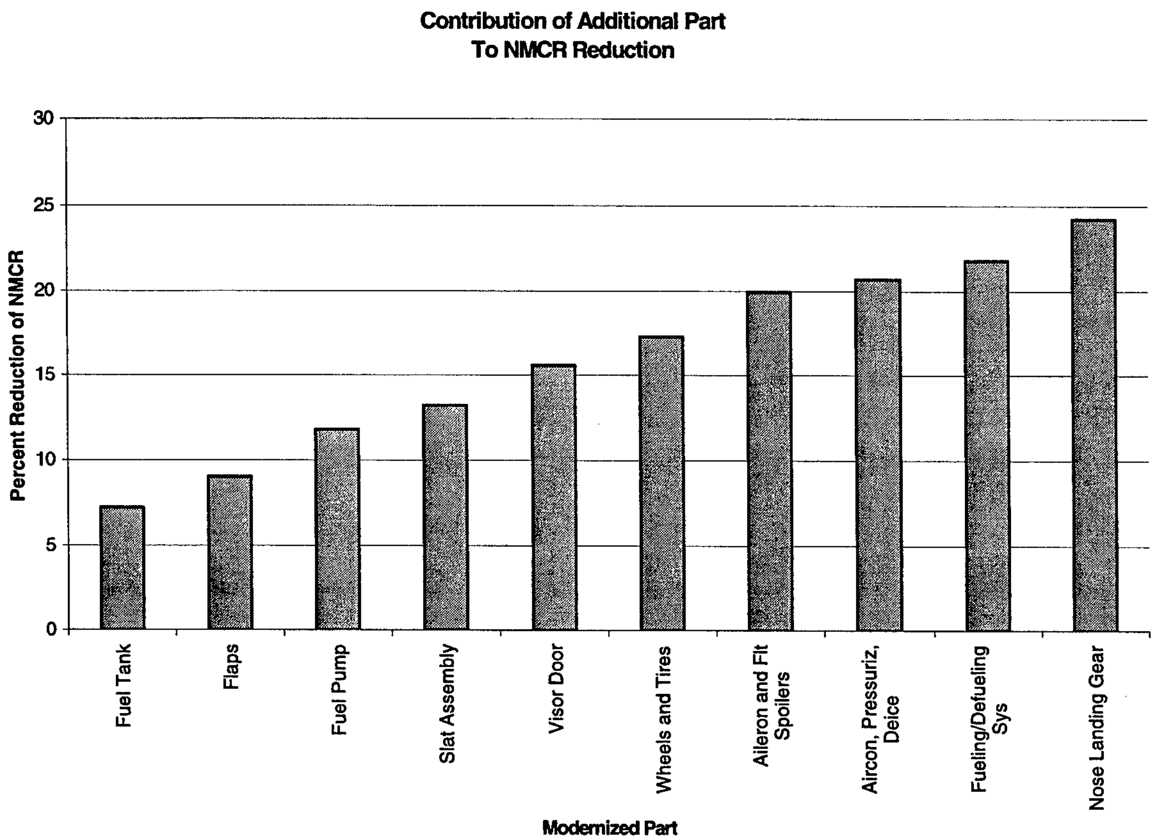


Figure 41. Impact of Additional Modernization on NMCR

Table 85. Additional Modernization Items to Improve MCR

Rank	Part	System	Description
1	46A	Fuel System	Fuel Tank
2	14J	Flight Controls	Flaps
3	46B	Fuel System	Fuel Pump
4	14L	Flight Controls	Slat Assembly
5	11B	Air Frame	Visor Door
6	13L	Landing Gear	Wheel and Tires
7	14A	Flight Controls	Ailerion and Flt Spoilers
8	41A	Aircon, Pressuriz, Deice	Aircon, Pressuriz, Deice
8	46H	Fuel System	Fueling/Defueling Sys
10	13B	Landing Gear	Nose Landing Gear

To reflect modernization, the failure rate of the modernized part was reduced by 90 percent while the downtime remained constant. The relative reduction of NMCR for each part being modernized is shown in Figure 43. The MCR model results indicate that if all 10 items are modernized, the NMCR can be reduced by as much as 24 percent.

III. OPERATING & SUPPORT COST ANALYSES

In this document we have estimated the costs and associated schedules to acquire each of the alternative aircraft configurations and to operate them until 2040. Of central interest are the operating and support (O&S) costs over this period of time and the disposal costs or residual values resident in the aircraft in 2040. We developed cost estimates using available data, information from historical studies, service estimates, and independent IDA assessments, as appropriate. Specific tools used to estimate the cost components and to develop schedules include cost estimating relationships, analogies, and bottom-up analyses. Because of the complexity of the O&S assessments, in this section we collect the main assumptions made and the results that are used elsewhere in this document. A comparable level of detail is available on the acquisition cost assumptions and results. Because the acquisition costs tend to involve company-sensitive information, these are found in Volume II, Appendix A.

A. O&S COST

Operating costs accumulate through FY 2040 to such an extent that they represent 70 percent or more of the total life cycle cost. We explain our approaches to estimating O&S costs in this section.

The O&S costs developed here represent the marginal or incremental costs incurred to operate and support the C-5 and C-17 aircraft configurations in each AoA alternative over the assessment period. The entire C-5 O&S cost is estimated for each alternative, but for C-17s we include only the O&S cost associated with any C-17s to be acquired beyond the programmed 135. In estimating O&S costs, we used the cost element structure defined in the Operating and Support Cost Estimating Guide published by the Office of Secretary of Defense Cost Analysis and Improvement Group (CAIG) dated May 1992. That cost element structure is shown in Table 86.

Table 86. O&S Cost Element Structure

Mission Personnel
Operations
Maintenance
Other
Unit-Level Consumption
Petroleum, Oil & Lubricants (POL)
Consumables
Depot-Level Repairables
Other
Depot Maintenance
Airframe Overhaul
Engine Overhaul
Other
Contractor Support
Sustaining Support
▪ Support Equipment Replacement
▪ Modification Kit Procurement/Installation
▪ Sustaining Engineering
▪ Post-Deployment Software Support
▪ Simulator Operations
Indirect Support
▪ Personnel Support
▪ Installation Support

We used a variety of techniques to obtain O&S costs. Some employed standard approaches, but others required unique or "tailored" methodologies. A summary review of the methods used for the C-5 and C-17 are provided in Table 87 and are discussed below.

Table 87. Methodology for Different O&S Categories

Cost Element	CORE Model	Propulsion Estimates	Other C-5 Improvements	C – 5 Structures	C-17 CLS	C-17 Structures
Mission Personnel						
- Operations	•					
- Maintenance	•					
Unit-Level Consumption						
- POL		•				
- Consumables	C-17 common	•	•		•	
- Depot-Level Reparables	C-17 common	•	•		•	
Depot Maintenance						
- Airframe Overhaul	•			•	•	•
- Engine Overhaul		•				
Contractor Support					•	
Sustaining Support						
- Support Equipment Replacement			•		•	
- Modification Kit Procurement/ Installation	•					
- Sustaining Engineering	C-5				•	
- Post Deployment Software Support	C-5				•	
- Simulator Operations	•				•	
Indirect Support						
- Personnel Support	•					
- Installation Support	•					

We used tailored O&S assessment methodologies to estimate the costs of the following: propulsion subsystem, aircraft structure maintenance, and C-5 reliability and maintainability improvements other than the propulsion system. Where a tailored assessment methodology was not used, we used the Air Force CORE model and cost information from Air Force Instruction (AFI) 65-503 and from Air Forces Total

Ownership Cost (AFTOC) in order to estimate other costs. To estimate sustaining engineering and software support, we used information from AFTOC and budget data from AMC. We also assessed the effects of C-5 improvements on manpower and aircraft maintenance costs. Last, we assessed the cost impact of changing to an annual letter check program for scheduled aircraft maintenance in lieu of isochronal inspections and refurbishment at the base level and of PDM at the depot.

For the C-17, we assessed the critical costs using tailored methods for contractor logistics support (CLS), structures, reserve component staffing, and the propulsion system. The CLS costs were derived using actual and estimated Flexible Sustainment costs provided by Boeing and the C-17 Program Office. Boeing projections were compared to current Flexible Sustainment experience and adjusted for anticipated increases in aircraft depot maintenance costs to keep the aircraft healthy through FY 2040. The adjusted flexible sustainment costs were estimated as CLS costs per flying hour and were included in the CORE model estimates. We estimated engine maintenance costs using the same methodology as that applied to the C-5 propulsion system. These were identified and tracked separately. Several of the alternatives included additional C-17 aircraft operating in Air Force Reserve (AFR) and Air National Guard (ANG) units. Since the ANG is planning to stand-up a C-17 unit, both AFR and ANG crew and maintenance staffing were estimated using ANG projections of staffing requirements and HQ AMC crew ratio requirements.

1. C-5 Operating and Support Costs

We summarize first the O&S cost estimate for flying hour failure-related elements and support equipment elements. Next we treat the propulsion system O&S. Finally, we assess other cost elements in the CORE model. Details can be found in Volume II, Appendix A, especially for proprietary propulsion system assumptions.

a. C-5 Flying Hour Failure-Related and Support Equipment O&S Estimates

This section deals with the costs of Bulk Supply (GSD), Consumable Parts and Depot Level Reparables (MSD), and Support Equipment Replacement (SE) for the various C-5 configurations defined in the alternatives, *with the exception* of costs in these categories that are associated with engines. Engine O&S costs are addressed separately.

The methodology used to develop our estimate entailed

- Developing a C-5 baseline cost for these items
- Evaluating projected reliability improvements associated with proposed upgrades
- Assessing the cost per flying hour (CPH) savings resulting from improved reliability
- Calculating the upgraded C-5A and the C-5B costs for these same items
- Phasing the costs to account for the different implementation schedules associated with the various alternatives.

b. Baseline Cost

The C-5 baseline costs were developed using cost data provided by the AFCEAA and using PAA, TAI, and flying hour data provided by AMC. Their cost data contained cost per hour (CPH) and cost per aircraft (CPA) for various cost categories by Major Command (MAJCOM) and aircraft type (MDS) for combinations of years ranging from 1999 through 2006. The AMC PAA, TAI, and flying hour data were organized in a similar fashion.

The analyses are lengthy and involve judgments about different data sources. Details can be found in Volume II, Appendix A. In Table 88 we summarize our calculation of the non-engine cost baseline, the baseline we deal with in this section. GSD and MSD are stated in CPH and SE is in terms of CPA.

Table 88. Non-Engine Baseline

		Non Engine Percent		Non Engine CPH/CPA	
Item	Total CPH/CPA ($)	C-5A (%)	C-5B (%)	C-5A ($)	C-5B ($)
GSD	918	87.56	88.93	804	816
MSD	2,852	90.05	88.41	2,568	2,522
SE	138,565	87.56	88.93	121,328	123,225

c. Reliability Improvements

We estimated the current cost savings associated with proposed C-5 improvements using reliability improvement data that were generated in our earlier C-5 analysis. It is appropriate, therefore, to briefly review how these data were derived.

Lockheed engineers made estimates of reliability improvements in terms of inherent failure rates. In most cases, there was reasonable rationale or data, but for several the major justification was "engineering judgment." We made several adjustments to the initial reliability improvements, supplying our own engineering judgment as necessary. In addition, we noted that the improvements were tied to only the IME (failure) rates. After examining detailed data provided to us by the Air Force, we found a considerable amount of Type 6 or induced failures, those caused by failure of other items or caused by maintenance. Applying a methodology that used the actual ratio of induced to total failures for the item being modified (excluding engines), we adjusted the Lockheed improvement factor for each of the items being upgraded. The results of these adjustments, in terms of saved MMH and IME are summarized in Tables 89 (for C-5A) and 90 (for C-5B).

Table 89. C-5A Savings in MMH and IME Resulting from Reliability Improvements

MMH/1000 FH [a]			IME/1000 FH[b]		
Pre-Upgrade	Savings	Post-Upgrade	Pre-Upgrade	Savings	Post-Upgrade
3995	2297	1698	376	226	150

[a] Maintenance Man hours per 1,000 flying hours

[b] Inherent maintenance event per 1,000 flying hours

Table 90. C-5B Savings in MMH and IME Resulting from Reliability Improvements

MMH/1000 FH [a]			IME/1000 FH [b]		
Pre-Upgrade	Savings	Post-Upgrade	Pre-Upgrade	Savings	Post-Upgrade
1788	1190	598	152	103	48

[a] Maintenance Man hours per 1,000 flying hours

[b] Inherent maintenance event per 1,000 flying hours

We have broken the savings down into two categories: Other Improvements and Other Engine Improvements. The reason being that there are two upgrade alternatives: a full upgrade that includes engines, and a partial upgrade that does not include engines. Although we have stressed that the engine upgrade *per se* is being treated separately, certain items in this section, e.g., pylons, will only be upgraded if the engine itself is replaced. In the case of the full upgrade we use the total savings in MMH and IME to adjust CPH and CPA; however, in the case of the partial upgrade we use only those MMH and IME savings associated with the category "Other Improvements."

d. Unit Savings & Costs

The following series of tables show how the data are used to estimate the dollar savings per unit (flying hours in the case of GSD and MSD, and aircraft in the case of SE) expected from the projected reliability improvements resulting from C-5 upgrades. They also show how these savings are used to compute the remaining *unit cost*, which, in conjunction with flying hours, is used to calculate a per-aircraft cost.

Table 91 shows for the C-5A how we use the percent of MMH and IME before any improvements to allocate the baseline unit cost for GSD, MSD, and SE among the three categories shown in the first column. We note that GSD and SE are calculated as a function of MMH, while MSD is calculated as a function of IME.

Table 91. C-5A Baseline CPH and CPA

Category	MMH	% MMH	IME	% IME	GSD Per Fly Hr ($)	MSD Per Fly Hr ($)	SE per Aircraft
Total	49,102		2,016		804	2,569	121,328
Other Improvements	3,179	6.47	315	15.63	52	401	18,959
Other Engine Improvements	816	1.66	61	3.03	13	78	3,671
All Else	45,107	91.86	1,640	81.35	738	2,090	98,698

In Table 92 we show how we use the anticipated savings in MMH and IME resulting from reliability improvements to calculate dollar savings in unit costs for the improved items.

Table 92. C-5A Savings in CPH and CPA

Category	MMH	% MMH Saving	IME	% IME Saving	GSD Per Fly Hr ($)	MSD Per Fly Hr ($)	SE per Aircraft
Total	49,102		2,016		804	2,569	121,328
Savings							
Other Improvements	1,709	3.48	181	8.98	28	231	4,222
Other Engine Improvements	589	1.20	45	2.22	10	57	1,455
Total Savings					38	288	5,677

Table 93 shows the results of subtracting the savings shown in Table 92 from the costs shown in Table 91 to compute new unit costs for both a full and a partial upgrade. This process requires some explanation. At first glance it appears that the unit costs for improved items are less after a partial upgrade than after a full upgrade. That's because with a full upgrade we include the net costs (costs in Table 91 less savings in Table 92) for "Other Engine Improvements" as part of costs shown for "Improved Items"; however, in the case of a partial upgrade, we use only the net cost for "Other Improvements" and add the *baseline* cost for "Other Engine Improvements" to the category "All Else" to reflect the fact that these items are not being improved.

Table 93. C-5A CPH and CPA for Full and Partial Upgrade

Category	Full Upgrade ($)			Partial Upgrade ($)		
	GSD Per Fly Hr	MSD Per Fly Hr	SE per Aircraft	GSD Per Fly Hr	MSD Per Fly Hr	SE per Aircraft
Improved Items	28	192	16,953	24	171	14,736
All Else	738	2,090	98,698	752	2,167	102,369
Total	766	2,281	115,651	776	2,338	117,106

In Table 94 we show the results of applying the unit costs from Table 93 to the projected annual flying hours per PAA aircraft (483) to arrive at the estimated annual "Other O&S" cost for each C-5A PAA aircraft under either upgrade option. The same results on a TAI basis are in Table 95.

Table 94. C-5A Cost per PAA Aircraft Flying 438 Hours Annually

Cost	Full Upgrade ($)			Partial Upgrade ($)		
	Improved Items	All Else	Total	Improved Items	All Else	Total
Flying Hour	96,057	1,238,633	1,334,690	85,359	1,278,528	1,363,886
Per Aircraft	16,953	98,698	115,651	14,736	102,369	117,106
Total	113,010	1,337,331	1,450,341	100,095	1,380,897	1,480,992

Table 95. C-5A Cost per TAI Aircraft

Full Upgrade ($)			Partial Upgrade ($)		
Improvements	All Else	Total	Improvements	All Else	Total
98,319	1,163,478	1,261,797	87,083	1,201,380	1,288,463

Tables 96 through 100 show the results of similar calculations for the C-5B.

Table 96. C-5B Baseline CPH and CPA

Category	MMH	% MMH	IME	% IME	GSD Per Flying Hour ($)	MSD Per Flying Hour ($)	SE per Aircraft ($)
Total	30,224		1,096		816	2,522	123,225
Other Improvements	1,181	3.91	115	10.46	32	264	4,817
Other Engine Improvements	606	2.01	37	3.39	16	86	2,472
All Else	28,436	94.08	944	86.14	768	2,173	115,936

Table 97. C-5B Savings in CPH and CPA

Category	MMH	% MMH Savings	IME	% IME Savings	GSD Per Flying Hour ($)	MSD Per Flying Hour ($)	SE per Aircraft ($)
Total	30,224		1,096		816	2,522	123,225
Savings							
Other Improvements	719	2.38	74	6.75	19	170	2,931
Other Engine Improvements	471	1.56	29	2.69	13	68	1,919
Total Savings	1,190	3.94	103	9.43	32	238	4,850

Table 98. C-5B CPH and CPA for Full and Partial Upgrade

Category	Full Upgrade ($)			Partial Upgrade ($)		
	GSD Per Fly Hr	MSD Per Fly Hr	SE per Aircraft	GSD Per Fly Hr	MSD Per Fly Hr	SE per Aircraft
Improved Items	16	112	2,439	12	94	1,886
All Else	768	2,173	115,936	784	2,258	118,408
Total	784	2,284	118,375	797	2,352	120,294

Table 99. C-5B Cost per PAA Aircraft Flying 832 Hours Annually

Category	Full Upgrade ($)			Partial Upgrade ($)		
	Improvements	All Else	Total	Improvements	All Else	Total
Flying Hour Costs	106,216	2,446,545	2,552,761	88,359	2,531,317	2,619,676
Per Aircraft Cost	2,439	115,936	118,375	1,886	118,408	120,294
Total Cost	108,655	2,562,481	2,671,136	90,245	2,649,725	2,739,970

Table 100. C-5B Cost per TAI Aircraft

Full Upgrade ($)			Partial Upgrade ($)		
Improvements	All Else	Total	Improvements	All Else	Total
95,616	2,254,983	2,350,600	79,415	2,331,758	2,411,173

e. Maintenance Creep

We need to adjust our base year costs to take into account maintenance creep, gradual increase in maintenance costs over time as equipment gets older. These increases are the result of factors such as increasing failure rates and the reduced availability of replacement parts. Following Lockheed Martin, we have assumed a maintenance creep factor of 2 percent per year. This is also consistent with the creep in NMCR experienced by the C-5. For the baseline cost and those items that will not be improved under the various upgrade alternatives we allow costs to increase by 2 percent per year from FY 2005 through FY 2040. For those items that have been improved, we do not begin the 2 percent growth until the eleventh year following their improvement.

f. Propulsion

Here we summarize how we estimate the powerplant O&S costs, both for the baseline TF39 engine and for a new 60,000-pound thrust engine.

Baseline C-5 Propulsion System (TF39 Engine). The baseline C-5 engine O&S costs were estimated using current data on the TF39. The TF-39 baseline estimate assumes that the:

- HT-90 upgrade has been completed
- Improved overhaul maintenance concept that minimize O&S costs at the aircraft level continues to be implemented
- Increased use of simulator training program that reduces the number of touch and go landing during aircrew training is implemented by the Air Force
- Overhaul of the thrust reverser continues as standard policy.

Detailed discussion of the costing methodology and input data required to estimate the baseline C-5 engine O&S costs is given in Appendix B. Table 101 provides a summary of the input data required for estimating O&S costs for this engine.

Table 101. Input Data for Baseline C-5 Engine O&S Cost Estimates

Input Data	Full Fleet
Engine Flying Hours per Year (Installed)	523.5
Engine Flying Hours before Removal	2,000
% Overhaul / % Other Repair given Removal	85% / 15%
Total Cost per Overhaul & Other Repair	$745 / EFH
On Wing Maintenance Cost per Engine Flying Hour	10% of Overhaul Costs $69.50 / EFH
Thrust Reverser (TR) Overhaul Costs	$20 / EFH
Life-Limited Component Replacement Costs (average based on part by part estimate over 36 years)	$47 / EFH
Fuel cost per A/C Flying Hour	$3,057

Using the data in Table 101, the total engine O&S cost per engine flying hour (EFH) for the baseline C-5 including fuel is estimated to be approximately $1,646. This is for an average C-5 aircraft. For dividing the fleet into C-5A and C-5B, we estimate the number of engine cycles that each fleet generates based on their different flying hour programs and training profiles. This way we can estimate a cost per EFH for each. Table 102 provides the details of this calculation.

Table 102. Apportioning Costs to C-5A & C-5B

Category	Fleet	C-5A	C-5B
Flying Hours	66000	28938	37062
EFH	264000	115754	148246
EFH/Cyc	1.58	1.44	1.70
Cycles	167619	80371	87248
Total Cost	$ 434,544,000	$ 208,358,277	$ 226,185,723
Cost/EFH	$ 1,646	$ 1,800	$ 1,526

With these costs per flying hour, we estimate the costs for each of the alternatives once we know how many baseline C-5s are in the inventory by year for each of the alternatives that we are evaluating. In Table 103, we provide the inventory data for each alternative that we used to perform our calculations.

Table 103. Inventory of Baseline C-5s by Calendar Year for Fleet Alternatives

	Number Baseline C-5s in Inventory (No. C-5A / No. C-5B)									
	Year									
Alt	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013-2040
1, 2 & 3	76/50	76/50	76/50	76/50	76/50	76/50	76/50	76/50	76/50	76/50
4 & 5	76/44	76/32	76/14	76/0	76/0	76/0	76/0	76/0	76/0	76/0
6, 7 & 8	76/44	65/32	50/14	35/0	20/0	5/0	0/0	0/0	0/0	0/0
9	76/50	65/50	50/50	35/50	20/50	5/50	0/40	0/25	0/10	0/0

With these inventories, the cost per EFH, and the number of EFHs per year for each type of aircraft, we estimate the baseline C-5 engine O&S costs. There are several small adjustments to this basic approach. First, we adjust our estimates with a cost savings for maintenance when aircraft are being retired or upgraded. This savings accounts for the fact that the engines being removed from the aircraft leaving the fleet have some useful life left, thereby reducing the overhaul requirements for the year that they become available. Also, in Alternative 3, the baseline C-5Bs are changed to guard/reserve status as the upgraded C-5As enter the fleet. This results in additional cost savings for the C-5B fleets due to reduced flying hours. Table 104 provides the resulting baseline C-5 engine O&S cost (FY 2000) estimates for each of the alternatives.

Table 104. Engine O&S Cost Estimates (FY 2000 dollars) for Baseline C-5s by Calendar Year for Fleet Alternatives

Year	1, 2, & 3	4 & 5	6 & 7	8	9
2004	$ 433	$ 372	$ 342	$ 372	$ 433
2005	$ 433	$ 311	$ 269	$ 281	$ 371
2006	$ 433	$ 255	$ 238	$ 185	$ 286
2007	$ 433	$ 207	$ 207	$ 95	$ 213
2008	$ 433	$ 207	$ 175	$ 54	$ 186
2009	$ 433	$ 207	$ 100	$ 14	$ 159
2010	$ 433	$ 207	$ 29	$ -	$ 131
2011	$ 433	$ 207	$ -	$ -	$ 70
2012	$ 433	$ 207	$ -	$ -	$ 16
2013	$ 433	$ 207	$ -	$ -	$ -
2014	$ 433	$ 207	$ -	$ -	$ -
2015	$ 433	$ 207	$ -	$ -	$ -
2016	$ 433	$ 207	$ -	$ -	$ -
2017	$ 433	$ 207	$ -	$ -	$ -
2018	$ 433	$ 207	$ -	$ -	$ -
2019	$ 433	$ 207	$ -	$ -	$ -
2020	$ 433	$ 207	$ -	$ -	$ -
2021	$ 433	$ 207	$ -	$ -	$ -
2022	$ 433	$ 207	$ -	$ -	$ -
2023	$ 433	$ 207	$ -	$ -	$ -
2024	$ 433	$ 207	$ -	$ -	$ -
2025	$ 433	$ 207	$ -	$ -	$ -
2026	$ 433	$ 207	$ -	$ -	$ -
2027	$ 433	$ 207	$ -	$ -	$ -
2028	$ 433	$ 207	$ -	$ -	$ -
2029	$ 433	$ 207	$ -	$ -	$ -
2030	$ 433	$ 207	$ -	$ -	$ -
2031	$ 433	$ 207	$ -	$ -	$ -
2032	$ 433	$ 207	$ -	$ -	$ -
2033	$ 433	$ 207	$ -	$ -	$ -
2034	$ 433	$ 207	$ -	$ -	$ -
2035	$ 433	$ 207	$ -	$ -	$ -
2036	$ 433	$ 207	$ -	$ -	$ -
2037	$ 433	$ 207	$ -	$ -	$ -
2038	$ 433	$ 207	$ -	$ -	$ -
2039	$ 433	$ 207	$ -	$ -	$ -
2040	$ 433	$ 207	$ -	$ -	$ -
Total	$16,033	$7,961	$1,362	$1,001	$1,864

New Propulsion System. The fully upgraded C-5 engine O&S costs were estimated using the 60,000 pound class aggregate engine defined in Appendix B. The actual data before aggregation corresponds to the PW 4000, the CF6, and the RB211-524. To avoid discussing any particular engine, we aggregate all three into a notional high-thrust engine. We obtained the data used for these cost estimates by adjusting data from commercial applications to account for the differences between commercial and C-5 military engine usage. The detailed discussion of the costing methodology and input data required to estimate the fully upgraded C-5 engine O&S costs are given in Appendix B. Table 105 provides a summary of the input data required estimating O&S costs for this engine.

Table 105. Input Data for Fully Upgraded C-5 Engine O&S Cost Estimates

Input Data	Full Fleet Upgrade	Partial Fleet Upgrade (All Active)
Engine Flying Hours per Year (Including Spares)	523.5	741
Engine Flying Hours Per Engine Degradation Cycle	1.575	1.575
Engine Degradation Cycles before Overhaul	5200	5200
Cost Per Overhaul	$1,683,333	$1,683,333
On Wing Maintenance Cost per Engine Flying Hour	$12 / EFH	$12 / EFH
FOD/Maintenance Induced Failure Costs	$5 / EFH	$5 / EFH
Thrust Reverser (TR) Overhaul Costs (Inboard Engines Only)	$100,000 per 10,000 EFH	$100,000 per 10,000 EFH
Fuel cost per C-5 Flying Hour	$3,057	$3,057

Using the data in Table 105, the yearly O&S costs are computed for fully upgraded C-5s. These are in Table 106. Once the costs per year of operation are computed, the total C-5 engine O&S cost for a given fleet alternative by calendar year can be computed by appropriate combination of the yearly costs. An example of how this is performed is given in Table 107. For this example, Lot 1 of 10 active aircraft begins operation in 2004, and Lot 2 of 10 active aircraft begins operation in 2005.

Table 106. Fully Upgraded C-5 Engine O&S Costs by Year of Operation Estimates (Full Fleet Upgrade Flying Hour Rate)

Year of Operation	Cumulative Flying Hours	Cumulative Degradation Cycles	Overhaul Cost (4 engines)	On Wing Maintenance (4 engines)	FOD/Maint. Induced Failure Repair (4 Engines)	T/R Overhaul (2 Engines)	Fuel Costs	Total
1	524	332	$ -	$ 25,128	$ 10,742	$ -	$ 1,600,340	$ 1,636,210
2	1047	665	$ -	$ 25,128	$ 10,742	$ -	$ 1,600,340	$ 1,636,210
3	1571	997	$ -	$ 25,128	$ 10,742	$ -	$ 1,600,340	$ 1,636,210
15	7853	4986	$ -	$ 25,128	$ 10,742	$ -	$ 1,600,340	$ 1,636,210
16	8376	5318	$ 6,733,332	$ 25,128	$ 10,742	$ -	$ 1,600,340	$ 8,369,542
17	8900	5650	$ -	$ 25,128	$ 10,742	$ -	$ 1,600,340	$ 1,636,210
18	9423	5983	$ -	$ 25,128	$ 10,742	$ -	$ 1,600,340	$ 1,636,210
19	9947	6315	$ -	$ 25,128	$ 10,742	$ -	$ 1,600,340	$ 1,636,210
20	10470	6648	$ -	$ 25,128	$ 10,742	$ 200,000	$ 1,600,340	$ 1,836,210
35	18323	11633	$ -	$ 25,128	$ 10,742	$ -	$ 1,600,340	$ 1,636,210
36	18846	11966	$ -	$ 25,128	$ 10,742	$ -	$ 1,600,340	$ 1,636,210
37	19370	12298	$ -	$ 25,128	$ 10,742	$ -	$ 1,600,340	$ 1,636,210

In order to estimate the total fully upgraded C-5 engine O&S costs for each fleet alternative, we require the number of C-5s that will be upgraded in each calendar year for all of the alternatives. Table 108 lists this data for each alternative that we analyze.

Using the data in Table 108, we computed the estimates for the total fully upgraded C-5 engine O&S costs (FY 2000 $M) for each of these alternatives. The resulting cost estimates are given in Table 109.

Table 107. Example Fleet Full Upgraded C-5 Engine O&S Cost Estimate by Calendar Year

Year	Lot 1 O&S Cost By Year	Lot 2 O&S Cost By Year	Total O&S Cost by Year
2004	$ 16,362,097	$ -	$ 16,362,097
2005	$ 16,362,097	$ 16,362,097	$ 32,724,194
2006	$ 16,362,097	$ 16,362,097	$ 32,724,194
2018	$ 16,362,097	$ 16,362,097	$ 32,724,194
2019	$ 83,695,417	$ 16,362,097	$ 100,057,514
2020	$ 16,362,097	$ 83,695,417	$ 100,057,514
2021	$ 16,362,097	$ 16,362,097	$ 32,724,194
2022	$ 16,362,097	$ 16,362,097	$ 32,724,194
2023	$ 18,362,097	$ 16,362,097	$ 34,724,194
2038	$ 16,362,097	$ 16,362,097	$ 32,724,194
2039	$ 16,362,097	$ 16,362,097	$ 32,724,194
2040	$ 16,362,097	$ 16,362,097	$ 32,724,194

Table 108. Number of C-5s Upgraded by Calendar Year for Fleet Alternatives

Year Entering	Number of C-5s Upgraded							
	2004	2005	2006	2007	2008	2009	2010	2011
Alternative								
4 & 5	6	12	18	14				
6 & 7	6	12	18	18	18	18	18	18
8	6	12	18	14				

Table 109. Fully Upgraded C-5 Engine O&S Cost (FY00$) Estimates by Calendar Year for Fleet Alternatives

Year	4 & 5	6 & 7	8
2004	$ 14	$ 10	$ 14
2005	$ 41	$ 29	$ 41
2006	$ 82	$ 58	$ 82
2007	$ 114	$ 87	$ 114
2008	$ 114	$ 116	$ 114
2009	$ 114	$ 145	$ 114
2010	$ 114	$ 174	$ 114
2011	$ 114	$ 203	$ 114
2012	$ 114	$ 203	$ 114
2013	$ 114	$ 203	$ 114
2014	$ 114	$ 203	$ 114
2015	$ 158	$ 204	$ 158
2016	$ 201	$ 204	$ 201
2017	$ 244	$ 204	$ 244
2018	$ 216	$ 205	$ 216
2019	$ 118	$ 205	$ 118
2020	$ 120	$ 250	$ 120
2021	$ 119	$ 292	$ 119
2022	$ 116	$ 334	$ 116
2023	$ 116	$ 334	$ 116
2024	$ 116	$ 336	$ 116
2025	$ 116	$ 337	$ 116
2026	$ 116	$ 338	$ 116
2027	$ 160	$ 338	$ 160
2028	$ 202	$ 210	$ 202
2029	$ 244	$ 210	$ 244
2030	$ 215	$ 210	$ 215
2031	$ 116	$ 210	$ 116
2032	$ 117	$ 206	$ 117
2033	$ 118	$ 206	$ 118
2034	$ 120	$ 206	$ 120
2035	$ 119	$ 206	$ 119
2036	$ 116	$ 206	$ 116
2037	$ 116	$ 250	$ 116
2038	$ 116	$ 292	$ 116
2039	$ 160	$ 334	$ 160
2040	$ 245	$ 334	$ 245
Total	$ 4,968	$ 8,095	$ 4,968

g. Other CORE Elements

Here we address the remaining O&S cost elements presented in Table 110. In this table, the cost elements are identified and comments pertinent to the cost element and/or associated estimate are provided. Tailored estimates were developed for maintenance staffing, aircraft depot maintenance, modification kit procurement/installation, sustaining engineering, and software maintenance.

Table 110. O&S Cost Elements Addressed as CORE Elements

Cost Element	Comments
Unit Mission Personnel	
Aircrew	Used crew ratios directed by HQ/AMC
Maintenance	Estimated staffing based on information from staffing projections from HQ/AMC and ANG and reliability data provided by Lockheed Martin
Other Mission	Used AFI 65-503 staffing data to estimate
Aircraft Depot Maintenance (excludes propulsion)	Estimated based on information from WR-ALC on current PDM costs experience and projections and Lockheed Martin on proposed Letter Check Program
Modification Kit Procurement/Installation	Used CORE model algorithm and adjusted costs higher to sustain objective MCR
Support Investment	
Sustaining Engineering	Adjusted to sustain objective MCR
Software Maintenance Support	Estimated based on AMP program
Indirect Support	
Personnel Support	Used CORE model algorithms to estimate
Installation Support	Used CORE model algorithms to estimate

The methods and sources of data used to estimates these costs and the cost estimates derived using these methods are described in full in Volume II, Appendix A and are summarized here.

C-5 Active Unit Staffing. We summarize in Table 111 the active aircrew staffing requirements for a typical C-5 wing with 32 PAA.

Table 111. C-5 Active Aircrew Staffing Requirements for a Typical Active 32 PAA Wing

Crew Ratio Calculation	
1. PAA x Crew Ratio = No. of Crews	
2. No. of Crews x Crew compliment (each crew position) = Crew Members	
Note: All calculations, round up	
1. 32 PAA x 1.8 Crew Ratio = 57.6 = 58 Crews	
2. 58 crews x 2 each pilots (011XX) =	116 pilots
58 crews x 2 each Flight Engineers (1a1X1) =	116 Flight Engineers
58 Crews x 2.5 load Masters (1A2X1) =	145 load masters
Total 377 Crew positions at a 32 PAA Active Duty wing	

In Table 112 we portray the current maintenance staffing for a C-5 active wing, using data provided by HQ AMC.

Table 112. C-5 Maintenance Staffing Requirements and Base Operating Staffing Factors for a Typical Active 32 PAA Wing

Maintenance Staffing Requirements		
Location	**No. of personnel**	**Comments**
Flight Line*	610	(Flight Line maintenance squadrons)
Maintenance Squadrons**	512	(Component Repair Squadron & Engine Maintenance Squadron)
Logistics Support Staff	61	
Supply***	58	
MOCC	30	Maintenance Operations Control center (MOCC)
Logistics Group	34	(This represents the Logistics Group overhead and Quality Assurance)
Total****	1305	
*68 of these positions are for flight-line engine support ** 98 of these positions are for 3-level back-shop engine maintenance. The current LCOM computes 40 of these positions as the requirement for 2-level engine maintenance. *** This portion of Supply is paid from the program element. **** Total does not account for following enroute maintenance spaces (32 PAA x 6.97 SPA = 223)		
Base Operations Support Computations		
BOS Tail = 8% x Hard-line Requirements		
Breakout of BOS Tail: Officer = BOS Tail x 1% Enlisted = BOS Tail x 75% Civilian = BOS Tail x 24%		

Active Units Maintenance Staffing. In developing adjustments to the maintenance staffing requirements, we used the information in Table 113 and the reliability estimates from Table 114 for the C-5A and from Table 115 for the C-5B to assess maintenance staffing requirements. The current aircraft configurations and projected aircraft configurations indicate that the C-5A and C-5B are clearly two different aircraft from a reliability perspective; however, we should be careful in attributing the differences between the two aircraft only to inherent aircraft characteristics. A significant portion of the difference could be associated with having about two-thirds of the C-5A aircraft assigned to the Air Reserve Components (ARC). When compared to the active component, the ARC have significantly different peacetime flying hour programs, which are dominated by training missions, skill levels of maintenance personnel, and policies and approaches to maintenance of the aircraft.

HQ AMC provided assessments of the effects of improvements on staffing requirements. This assessment is provided in Table 113. The letter check approach to aircraft-level isochronal inspections and repairs, PDM, and refurbishment would eliminate the requirement for the HQ/AMC staffing to perform isochronal inspections as a part of PDM at Warner Robins ALC. This reduces the staffing requirements by 75 personnel. The AMP and elimination of the isochronal inspection would remove the need for avionics and isochronal backshops at the two active bases, thereby reducing active staffing and Associate Reserve maintenance staffing by 48 and 45 positions, respectively. The new engines would reduce the propulsion backshop by a total of 18 active positions and 5 Associate Reserve positions. The letter check would also eliminate 35 active positions that perform the refurbishment inspections.

Table 113. HQ/AMC Assessment of Effects of Various C-5 Improvements on Maintenance Staffing

Description	Rationale	Active				Air Reserve Component			
		Total	Officer	Enlisted	Civilian	Total	Officer	Enlisted	Art
Eliminate Warner Robins ALC Inspection Element	Contract Letter Checks	75	1	74	0	0			
Eliminate Avionics & Isochronal Backshops	Avionics Upgrade And Elimination Of Isochronal Inspection	48	0	32	16	45		12	33
Decrease Propulsion Backshops[a]	Increase Engine Reliability	18	0	12	6	5			5
Eliminate Refurbishment Inspection[b]	Contract Letter Checks	35	0	35	0	0			
Total Maintenance		176	1	153	22	50	0	12	38

[a] Decrease Engine Removal Rate By 90% Baseline Is 88

[b] 15 @ Travis and 20 @ Dover (Includes Stewarts)

In addition to using HQ AMC information in our analysis, we also assessed the staffing requirements using a methodology that relates reliability improvements to staffing requirements. The measure of reliability used is the failures per 1,000 flying hours. The baseline reliability for all unmodified segments of the aircraft were derived from actual historical experience for the past 3 years. For all improvements including projected reliability for the high high-pressure turbine modification (HT-90) to the TF39 engine, which has been approved for incorporation into the current C-5 aircraft, we used failure data provided by Lockheed Martin. In Table 114 for the C-5A and Table 115 for the C-5B the failure rate projections are presented for the following aircraft configurations:

- Current configuration with the HT-90 modification
- Baseline configuration, which includes both the HT-90 modification and the AMP improvements
- Partial upgrade, which includes all proposed modifications except those for the propulsion system
- Full upgrade, which includes all proposed modifications to the C-5 aircraft.

Table 114. C-5A Inherent Failures Rates for Alternative Aircraft Configurations

Aircraft Configuration	Failure Rate per 1,000 Flying Hours for Aircraft Modifications				
	AMP	Other Mods	Propulsion	Unmodified	Total Reliability
Current with HT-90	119.5	375.3	292.9	1085.9	1873.6
Baseline	17.3	375.3	292.9	1085.9	1771.4
Partial Upgrade	17.3	131.6	292.9	1085.9	1527.7
Full Upgrade	17.3	131.6	40.5	1085.9	1275.3

For the C-5A, the current estimate is a reduction from 1,874 failures per 1,000 flying hours to 1,275 failures when comparing the current aircraft configuration to the full upgrade configuration of the C-5A.

Table 115. C-5B Inherent Failures Rates for Alternative Aircraft Configurations

Aircraft Configuration	Failure Rate per 1000 Flying Hour for Aircraft Modifications				
	AMP	Other Mods	Propulsion	Unmodified	Total Reliability
Current with HT-90	119.5	196.3	184.3	524.3	1024.4
Baseline	17.3	196.3	184.3	524.3	922.2
Partial Upgrade	17.3	93.4	184.3	524.3	819.3
Full Upgrade	17.3	93.4	34.2	524.3	669.2

For the C-5B, the current estimate is a reduction from 1,024 failures per 1,000 flying hours to 669 failures when comparing the current aircraft configuration to the full upgrade configuration of the C-5B.

These reductions in failure rates, when combined with the changes in maintenance concepts such as eliminating the avionics intermediate maintenance shop and reducing staffing in the engine intermediate maintenance shop (propulsion system upgrade), should allow for a reduction in maintenance staffing requirements for both the C-5A and C-5B.

Using the staffing adjustment methodology portrayed in Table 116, we assessed the effects of the reliability improvements on the staffing requirements. We developed a derated staffing factor based on the fact that maintenance staffing is driven by factors in addition to inherent reliability, such as repair times, training requirements, other military duty requirements, and requirements to support the enroute structure of the aircraft. Using this methodology for an active unit with a mix of C-5A and C-5B aircraft, we predict a 2-percent reduction of staffing requirements when the Baseline configuration is deployed, a 7-percent staffing reduction for the Partial Upgrade and a 12 percent reduction in the case of a Full Upgrade.

Table 116. Effects on Active Maintenance Staffing as the Results of Improvements to C-5 Aircraft

Factor	Current With HT 90	Baseline (Current + AMP)	Partial	Full
C-5A – Inherent Failures/1000 FH	1874	1771	1528	1275
Failures - % of Current A/C		0.95	0.82	0.68
C-5B – Inherent Failures/1000 FH	1024	922	819	669
Failures - % of Current A/C		0.90	0.80	0.65
Weighted C-5A & C-5B: Failures - % of Current A/C		0.92	0.81	0.66
Estimated Reduction in Staffing %		1.6	6.6	11.8

The final staffing adjustments applied to an active C-5 wing for each C-5 configuration is provided in Table 117. This table portrays the current, baseline (which includes the AMP), letter check, partial upgrade and full upgrade staffing requirements. To derive these staffing adjustments, we used a combination of the information provided by HQ AMC on the effects of C-5 improvements on staffing requirements as portrayed in Table 113 and the reliability and maintainability information as portrayed in Table 117. The staffing adjustments were calculated based on reducing the number of maintenance spaces per aircraft from the staffing in a current C-5 wing to the baseline configuration, which includes the AMP improvements. Next, an estimate for the maintenance spaces per aircraft that includes the effects of a change to a letter check aircraft maintenance concept is estimated. Next the effects of a partial upgrade are assessed and finally an estimate for the full upgrade is derived.

Table 117. Specific Staffing Adjustments Implemented in O&S Estimate by C-5 Aircraft Configurations & Maintenance Concepts

Activity	Current		Baseline (AMP)		Letter Check		Partial		Full	
Maintenance Organization	No. spaces	Spaces /ac	No. spaces	Spaces /ac	No. spaces	Spaces /ac	No. spaces	spaces /ac	No. spaces	spaces /ac
AGS	610	19.06	604	18.87	604	18.87	592	18.49	585	18.28
MXS SQ	512	16.00	499	15.60	453	14.16	444	13.87	386	12.06
LSS	61	1.91	60	1.87	59	1.83	57	1.79	56	1.76
Supply	58	1.81	57	1.78	56	1.74	55	1.71	53	1.67
MOCC	30	0.94	30	0.94	30	0.94	30	0.94	30	0.94
Log Group	34	1.06	34	1.06	34	1.06	34	1.06	34	1.06
Total	1305	40.78	1284	40.12	1235	38.60	1212	37.87	1145	35.77
Enroute	223	6.97	219	6.86	219	6.86	215	6.73	203	6.35
Total	1528	47.75	1503	46.97	1455	45.46	1427	44.59	1348	42.13
2nd Wing	1528	47.75	1503	46.97	1455	45.46	1427	44.59	1348	42.13
Percent of Current Staffing				0.984		0.952		0.934		0.882
Robins Inspection Element	75		75		0		0		0	
Total	3179		3081		2909		2854		2696	

C-5 Reserve Associate Unit Staffing. This segment addresses the Reserve Associate unit staffing estimates used in the O&S cost estimates for the various configurations of C-5 A/B aircraft. In developing the estimate, we used the current staffing information available in AFI 65-503 as the basis for our estimates. We present in Table 118 the total Primary Program Element (PPE) staffing requirements for a Reserve Associate aircrew and maintenance staffing requirements. The AFI 65-503 aircrew staffing was used without change in our study for all configurations of aircraft. The maintenance staffing was adjusted to reflect expected improvements in reliability and maintainability of the improved C-5A and C-5B aircraft configurations. Table 118 portrays for the C-5A and C-5B the current, baseline, partial upgrade, and full upgrade PPE staffing requirements. The maintenance staffing requirements were derived using the staffing effects cited in Table 116 to estimate the Reserve Associate maintenance staffing adjustments. To illustrate, the reductions from the current configuration for both the C-5A and C-5B were approximately 2 percent for the baseline configuration, 7 percent for the partial upgrade, and 12 percent for the full upgrade.

Table 118. Air Force Reserve Associate Staffing Including Specific Staffing Adjustments Implemented in O&S Estimate by C-5 Aircraft Configurations

Personnel	C-5B Associate Current C-5B	C-5B Associate Baseline C-5B	C-5B Associate Partial C-5B	C-5B Associate Full C-5B	C-5A Associate Current C-5A	C-5A Associate Baseline C-5A	C-5A Associate Partial C-5A	C-5A Associate Full C-5A
PAA	16	16	16	16	16	16	16	16
Crew Ratio	2	2	2	2	2	2	2	2
FH/PAA/YR	0	0	0	0	0	0	0	0
Pilots/Crew	2	2	2	2	2	2	2	2
Non-Pilot Off/Crew	0	0	0	0	0	0	0	0
Enl/Crew	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
II Manpower Factors (Staff Position)								
PPE Total	962	962	945	912	962	962	945	912
PPE Drill Officers	84	84	84	84	84	84	84	84
PPE Drill Enlisted	723	723	716	711	723	723	716	711
PPE Civilian Techs	15	15	15	15	15	15	15	15
PPE Civilians	140	140	130	102	140	140	130	102
BOS Drill Officers	11	11	10	10	11	11	10	10
BOS Drill Enlisted	21	21	20	19	21	21	20	19
BOS Civilian Techs	10	10	10	10	10	10	10	10
BOS Civilians	11	11	10	10	11	11	10	10
RPM Drill Enlisted	5	5	5	5	5	5	5	5
RPM Civilian Techs	2	2	2	2	2	2	2	2
RPM Civilians	6	6	6	5	6	6	6	5
Unit Staff Drill Officers	12	12	12	12	12	12	12	12

C-5 Reserve Unit Staffing. This segment addresses the Reserve unit staffing estimates used in the O&S cost estimates for the various configurations of C-5 A/B aircraft. In developing the estimate, we used the current staffing information available in AFI 65-503 as the basis for our estimates. We present in Table 119 the total PPE staffing requirements for a Reserve units aircrew and maintenance staffing requirements. The AFI 65-503 aircrew staffing was used without change in our study for all configurations of aircraft. The maintenance staffing was adjusted to reflect expected improvements in reliability and maintainability of the improved C-5A and C-5B aircraft configurations. Table 119 portrays for the C-5A and C-5B the current; baseline, which includes the AMP; partial upgrade; and full upgrade PPE staffing requirements. The maintenance staffing requirements were derived using the staffing effects cited in Table 116 to estimate the Reserve unit maintenance staffing adjustments. To illustrate, the reductions from the current configuration for both the C-5A and C-5B were 2 percent for the baseline configuration, 7 percent for the partial upgrade, and 12 percent for the full upgrade.

Table 119. Air Force Reserve Unit Staffing Including Specific Staffing Adjustments Implemented in O&S Estimate by C-5 Aircraft Configurations

Personnel	C-5B AFR Current C-5B	C-5B AFR Baseline C-5B	C-5B AFR Partial C-5B	C-5B AFR Full C-5B	C-5A AFR Current C-5A	C-5A AFR Baseline C-5A	C-5A AFR Partial C-5A	C-5A AFR Full C-5A
PAA	14	14	14	14	14	14	14	14
Crew Ratio	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
FH/PAA/YR	325	325	325	325	325	325	325	325
Pilots/Crew	2	2	2	2	2	2	2	2
Non-Pilot Off/Crew	0	0	0	0	0	0	0	0
Enl/Crew	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
II Manpower Factors (Staff Positions)								
PPE Total	1821	1821	1756	1733	1821	1821	1756	1733
PPE Drill Officers	91	91	91	91	91	91	91	91
PPE Drill Enlisted	1131	1131	1120	1112	1131	1131	1120	1112
PPE ARTs	550	550	531	517	550	550	531	517
PPE Civilians	49	49	47	46	49	49	47	46
BOS Drill Officers	19	19	19	18	19	19	19	18
BOS Drill Enlisted	31	31	30	30	31	31	30	30
BOS Civilian Techs	4	4	4	4	4	4	4	4
BOS Civilians	9	9	9	9	9	9	9	9
RPM Drill Officers	0	0	0	0	0	0	0	0
RPM Drill Enlisted	6	6	6	5	6	6	6	5
RPM Civilian Techs	5	5	5	5	5	5	5	5
Unit Staff Drill Enlisted	12	12	12	12	12	12	12	12

C-5 Air National Guard Unit Staffing. This segment addresses the Air National Guard unit staffing estimates used in the O&S costs estimates for the various configurations of C-5 A/B aircraft. In developing the estimate, we used the current staffing information available in AFI 65-503. We present in Table 120 the total PPE staffing requirements for a Reserve unit aircrew and maintenance staffing requirements. The AFI 65-503 aircrew staffing was used without change in our study for all configurations of aircraft. The maintenance staffing was adjusted to reflect expected improvements in reliability and maintainability of the improved C-5A and C-5B aircraft configurations. Table 120 portrays for the C-5A and C-5B the current; baseline, which includes the AMP; partial upgrade; and full upgrade PPE staffing requirements. The maintenance staffing requirements were derived using the staffing effects cited in Table 116 to estimate the Air National Guard unit maintenance staffing adjustments. To illustrate, the reductions from the current configuration for both the C-5A and C-5B were approximately 2 percent for the baseline configuration, 7 percent for the partial upgrade, and 12 percent for the full upgrade.

Table 120. Air National Guard Unit Staffing Including Specific Staffing Adjustments Implemented in O&S Estimate by C-5 Aircraft Configurations

Personnel	C-5B ANG Current C-5B	C-5B ANG Baseline C-5B	C-5B ANG Partial C-5B	C-5B ANG Full C-5B	C-5A ANG Current C-5A	C-5A ANG Baseline C-5A	C-5A ANG Partial C-5A	C-5A ANG Full C-5A
PAA	12	12	12	12	12	12	12	12
Crew Ratio	2	2	2	2	2	2	2	2
FH/PAA/YR	274	274	274	274	274	274	274	274
Pilots/Crew	2	2	2	2	2	2	2	2
Non-Pilot Off/Crew	0	0	0	0	0	0	0	0
Enl/Crew	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
II Manpower Factors (Staff Positions)								
Weapon System Total Staffing	1364	1364	1325	1303	1364	1364	1425	1303
Civilian Techs	345	345	342	339	345	345	342	339
AGR Officer	11	11	11	11	11	11	11	11
AGR Enlisted	120	120	116	112	120	120	116	112
Drill Officer	79	79	76	74	79	79	76	74
Drill Enlisted	809	809	781	760	809	809	781	760
BOS Civilian Techs	25	25	25	25	25	25	25	25
BOS AGR Officers	1	1	1	1	1	1	1	1
BOS AGR Enlisted	7	7	7	7	7	7	7	7
BOS Drill Officers	9	9	9	9	9	9	9	9
BOS Drill Enlisted	213	213	213	213	213	213	213	213
RPM Drill Officers	0	0	0	0	0	0	0	0
RPM Drill Enlisted	5	5	5	5	5	5	5	5
RPM AR Techs	2	2	2	2	2	2	2	2
RPM Civilians	6	6	6	6	6	6	6	6
Unit Staff Drill Enlisted	12	12	12	12	12	12	12	12

Aircraft Depot Maintenance. We estimated C-5 depot maintenance costs to reflect the change in the maintenance concept that moves the work performed in three types of aircraft scheduled maintenance activities, base-level isochronal inspections, refurbishment and depot-level programmed depot maintenance to a commercial type of aircraft maintenance concept. The commercial maintenance replaces the scheduled maintenance activities with an annual depot letter check program. Our approach to estimating the aircraft depot maintenance O&S costs is to derive a steady-state estimate that takes into account the potential for cost growth as the C-5 fleet ages. In the structure O&S cost segment that follows we estimated specific aircraft retrofit actions that will have to be accomplished to keep the structural integrity of the C-5 fleet healthy through 2040. Although a significant amount of the projected retrofit costs would be incurred in aircraft depot maintenance activities, those are over and above the costs projected in this segment. Also, the retrofit costs do not include the repair work needed to expand the structural inspections needed as the aircraft ages and to address corrosion problems, which cannot be easily predicted. In addition, other unpredictable structure repair actions are required to keep the fleet healthy. These costs are addressed in this estimate of aircraft depot maintenance costs.

Currently the C-5 aircraft depot maintenance is based on a programmed depot maintenance concept where a C-5A aircraft is inducted every 5 years and a C-5B is inducted every 7 years. The typical types of work performed during PDM include: Analytic Condition Inspection (ACI) annual tasks (ACI annual fix hours, ACI phased tasks, ACI phased fix hours) and depot-level maintenance tasks (incoming processing, depot tasks defined in a specified statement of work, over and above tasks, flight prep tasks, and delivery tasks.)

Programmed depot maintenance for the C-5 is in a period of transition as the work was recently transferred from San Antonio Air Logistics Center (SA-ALC) to Warner Robins Air Logistics Center (WR-ALC). The only actual cost experience at WR-ALC is for the first eight aircraft, which were C-5A aircraft, the oldest aircraft in the C-5 inventory. Table 121 presents the actual cost for each aircraft broken down by fixed-price labor for a specified work package, over-and-above costs for work that was performed but was not included in the fixed-price work specification, and material costs. Included in the over-and-above work is a significant effort to repair the horizontal stabilizer tie-box on the C-5A aircraft. The actual cost experience is accounted for at the cost level and does not allow a breakout of actual labor hours expended to perform the work.

Our baseline estimate is based on the assumption that the C-5A will continue to require a PDM every 5 years at this level of resource requirements. For the C-5B, our baseline estimated assumes that as the C-5B ages PDM period will shorten to 5 years and will require the same level of depot work as the C-5A on the average from now to 2040. The labor hour content was estimated based on the assumption that the cost per labor hour is $70 at WR-ALC. This results in an estimate of an average of 27,986 labor hours for fixed priced tasks and 11,577 labor hours for over-and-above tasks resulting in a total of 39,563 hours to perform PDM and related work on the C-5A. This compares to the previous estimate of 32,350 PDM labor hours for the C-5A at SA-ALC. The 39,563 hours were used to estimate both the C-5A and C-5B steady-state aircraft depot maintenance costs using the current maintenance concept and as the basis for estimating the costs of aircraft depot maintenance under a letter check maintenance concept.

Table 121. Warner Robins Air Logistics Center Programmed Depot Maintenance Costs (Experience for First Eight C-5A Aircraft)

Aircraft	Costs (in FY 2000 Dollars)			
	Fixed Price	Over & Above	Material	Total
C-5A	2,159,606	774,723	2,988,244	5,922,573
C-5A	1,674,739	841,346	2,732,658	5,248,743
C-5A	1,951,122	778,436	3,278,540	6,008,098
C-5A	1,919,793	713,343	2,743,381	5,376,517
C-5A	2,178,420	1,055,218	2,792,975	6,026,613
C-5A	2,198,144	633,252	3,769,319	6,600,715
C-5A	1,934,276	829,851	3,362,898	6,127,025
C-5A	1,655,925	856,712	2,630,905	5,143,542
Total	**15,672,025**	**6,482,881**	**24,298,920**	**46,453,826**
Cost Per Aircraft	1,959,003	810,360	3,037,365	5,806,728
Average Labor Rate/Hour	70	70		70
Labor Hours Per Aircraft	27,986	11,577		39,563
Annual Cost Per Aircraft	279,857	115,765	433,909	829,532

Source: *WR-ALC*

For both the partial and full upgrade configuration, we assumed that a modernized aircraft with improved systems and structural repairs should allow a transition to a commercial letter check maintenance concept. In a letter check process, the aircraft is sent to depot annually and the scheduled aircraft-level maintenance tasks previously performed at the base and depot are combined with a reduction in scope when compared to the current PDM. An example where significant scope reduction would occur is in the requirement to remove each engine pylon for inspection and repair as necessary during a PDM. This results in each aircraft having to pass a comprehensive flight check and significant final delivery work before returning to the operating command. Under a letter check concept the pylons could be removed one at a time over a 4-year period eliminating the requirement for the comprehensive flight check. A possible negative effect of the letter check concept is that the aircraft will have to undergo incoming depot processing and final delivery tasks on an annual basis. The scope of the final delivery tasks would be substantially reduced when compared to a normal PDM, but would still require an effort on an annual basis versus 1 every 5 or 7 years. Table 122 presents the Lockheed Martin estimate of what the labor hours would be when the maintenance tasks performed at the isochronal inspection, refurbishment, and PDM are combined to perform an annual letter check maintenance activity.

Table 122. Lockheed Martin Estimate of Letter Check Staff-Hours, and Days

Task	Total MH	Frequency	Estimated MH/year
Letter Check	6,458	Yearly	6,458
Paint	4,509	Every 10 years	451
Total			6,909
Aircraft Days in Letter Check and Paint			
	Total Days	Frequency	Average Days/year
Letter Check	14	Annual	14
Paint	12	Every 7 years	2
Total	26		16

In developing our estimate of the annual costs per aircraft for letter check, we estimated first the material costs, followed by our estimate of labor hours required. Our basic assumption is that the letter check work would be performed over a 6-year cycle, and the work performed in PDM, isochronal inspections, and refurbishment would be spread over 6 years. Our estimate of the material costs is presented in Table 123. These costs are based on the most recent WR-ALC PDM material costs reviewed above and include both in-scope work to the PDM specification and out-of-scope work needed to correct problems such as corrosion and other structure and system problems with the aircraft. From the estimated total costs for letter check material through FY 2040, we subtracted the $80,000,000 one-time lay-in of spare parts included in our acquisition program to ensure sufficient spare parts are available to meet the 21-day PDM specification work schedule. With the reduction for the one-time lay-in of spares and the work spread over 6 years versus 5 as currently required for the C-5A aircraft, our annual estimate of material costs per aircraft is reduced from the current experience of about $440,000 to about $182,000.

Table 123. Estimate of C-5 Letter Check Annual Material Costs

Item	Costs (FY 2000 dollars)
Estimated Total Material Costs Through FY 2040	$202,288509
Acquisition Material Lay-in in Production	$80,000,000
Remaining Material Cost	$122,288,509
Estimated Total Annual Material Cost	$3,821,515.90
Estimated Annual Material Cost Per Aircraft	$181,976.95

For the labor costs we developed an estimate of labor hours required to perform the work necessary for a letter check program. The baseline PDM hours of about 28,000 hours are consistent with the work projected for a C-5A aircraft at SA-ALC before transition to WR-ALC and includes over-and-above hours and modification/TCTO hours both greater than 1,000 hours. To this we have added over 9,000 hours of over-and-above work to capture work necessary for the refurbishment program, additional aircraft inspections, additional aircraft fatigue repairs, and corrosion repairs. We also project a commercial operation to perform this work and expect to receive benefits from a competitive procurement in two areas: a slight reduction of 5 percent in work content and a lower cost per labor hour to slightly over $61.38 per hour or about $127,670 per staff year. Our estimate is summarized in Table 124 and projects an annual letter check cost of about $543, 894 per aircraft per year.

Table 124. Estimated Annual Costs Per Aircraft for Letter Check Aircraft Maintenance Program FY 2000 Dollars

Category	Baseline PDM	Over and Above	Total
Total Hours Per PDM	28000	9240	37240
Hours/Year PDM @ 5 year cycle	5600	1848	7448
Letter Check Efficiency	0.95	0.95	0.95
Hours/Year Letter Check with 6 year cycle	4433	1463	5896
Cost Per Labor Hour	$61.38	$61.38	$61.38
Total Annual Labor Cost	$272,118	$89,799	$361,917
Material Cost			$181,977
Total Annual Letter Check Costs			$543,894

Modification Kit Procurement and Installation. The modification and kit procurement and installation O&S costs address the reliability, maintainability, and safety modifications needed to allow a weapon system to perform its original mission over its operating life. In the past, most aircraft O&S costs estimates have relied on the cost estimating relationship (CER) in the Air Force CORE model to predict modification kit procurement and installation costs. This CER is derived from historical cost experience of these types of modifications for aircraft programs. There is little supporting evidence that the CER is normative, providing the resources actually needed to sustain an aircraft over the operating life now projected for the C-5A/B. Furthermore, the model was derived when the aircraft were not being required to stay in service for their entire design life. In our estimate for the C-5A/B upgrade programs, we have started with the CER and adjusted modification costs upward to account for extending the operating life of the C-5A/B through 2040 or close to their design lives. In addition, our objective was to increase our confidence that the C-5A/B aircraft will be able to achieve the mission capability rate objectives defined in the AoA. We selected a 30-percent increase over the CER projected modification costs for the partial upgrade and a 20-percent increase for the full upgrade. The full-upgrade's increase is lower than that of the partial upgrade because the full-upgrade increased recurring flyaway cost and replaced propulsion system (including pylons and propulsion-system-related electrical systems) reduced the risk associated with the full upgrade configuration. Our estimate is portrayed in Table 125, which shows an increase in the modification costs for the full upgrade C-5B when compared to the current C-5B from about $358,000 to about $510,000 representing an increase of 40 percent.

Table 125. C-5 Modification Kit Procurement and Installation Cost Estimates

Category	Configuration			
	Current	Baseline	Partial	Full
C-5B Flyaway Cost $ Millions	$185	$189	$192	$230
Class IV Mod (Safety) Equation	357892	363904	369336	424687
Additional Increase for sustaining MCR	0	0	110801	84937
Annual Modification Requirement in $	357892	363904	480136	509624
C-5A Flyaway Cost	$158	$162	$165	$203
Class IV Mod (Safety) Equation	316161	322381	327996	385021
Additional Increase for sustaining MCR	0	0	98399	77004
Annual Modification Requirement in $	316161	322381	426394	462025

Sustaining Engineering. Sustaining engineering provides the engineering support necessary to ensure that a weapon system operates safely and effectively throughout its operating life. The tasks include problem definition for both hardware and software elements of the aircraft and for hardware problem resolution through studies, initial designs, breadboard prototypes, and/or engineering change proposals. As portrayed in Table 126, we used the Sustaining Engineering Costs from the Air Force Total Ownership Cost data base for FY 1998 as a basis to estimate these costs. We adjusted the cost per PAA per year by the ratio of the recurring flyaway costs to estimate the annual sustaining engineering requirements per PAA. We wanted sufficient sustaining engineering funds to support the aircraft throughout its operating life and to maintain the improved MCR needed to provide the mission effectiveness used in the operational analysis. Using these ratios we arrived at the following sustaining engineering costs per year for the current configuration of $98,686, baseline configuration of $100,805, partial upgrade of $128,412, and full upgrade of $153,470. This provided an increase of greater than 50 percent in sustaining engineering funds when comparing the full upgrade configuration to the experience with the current configuration.

Table 126. C-5A/B Sustaining Engineering Costs For FY 1998 from AFTOC Data Base I

Aircraft	Total Cost (in FY 2000 Dollars)	Cost per PAA(in FY 2000 Dollars)
C-5B	7,922,381	180,054
C-5A	2,933,025	44,440
C-5A/B	10,855,406	98,686

Software Support. We do not have an estimate for the size or complexity of the software that Lockheed Martin plans for the baseline configuration of the C-5A/B aircraft that includes the AMP. We estimated the software support costs at twice the current experience with the C-5 aircraft or an increase from about slightly over $6 million per year to over $12 million. At a yearly staffing cost of about $125,000, the $12 million would provide an annual staffing for about 100 software engineers to support the C-5 software.

2. C-17 Operating and Support Costs

This segment reviews the O&S costs for the C-17. In this segment, we first review the O&S costs for the propulsion system, then address the other CORE model costs that have been estimated for the C-17. These costs are combined into a total O&S cost estimate.

a. Propulsion: F117 Engine

C-17 engine O&S costs were estimated only for additional C-17s purchased beyond the current planned buy of 135 (120 baseline + 15 SOF) aircraft. All of these aircraft will have the latest DO-3 version of the P&W F117 engine. We used data for this engine on existing C-17s and on commercial aircraft with this engine to estimate engine O&S costs. Further discussion of the costing methodology and input data required for estimating the C-17 engine O&S costs is given in Appendix B. Table 127 provides a summary of the input data required for estimating O&S costs for this engine.

Table 127. Input Data for C-17 Engine O&S Cost Estimates

Input Data	Active/Training A/C	Guard/Reserve A/C
A/C Flying Hours per Year (PAA)	1470	700
A/C Flying Hours per Year (TAI)	1336	636
Engine Flying Hours per Engine Degradation Cycle	1.0	1.0
Engine Degradation Cycles before Overhaul	6180 (1st Run), 0.86180 (2nd, ... Runs)	6180 (1st Run), 0.86180 (2nd, ... Runs)
Cost per Overhaul	$1,200,000	$1,200,000
On Wing Maintenance Cost per Engine Flying Hour	10% of Mature OH Cost $24 / EFH	10% of Mature OH Cost $24 / EFH
Fuel Cost per A/C Flying Hour	$2,448	$2,448

Using the data in Table 127, the yearly O&S cost for both an Active and a Guard/Reserve C-17 aircraft are computed. An example of this estimate for an Active C-17 is given in Table 128.

Table 128. C-17 Engine O&S Costs by Year of Operation Estimates

Year of Operation	Cumulative Flying Hours	Cumulative Degradation Cycles	Overhauls Costs (4 engines)	On Wing Maintenance (4 engines)	Fuel Costs	Total
1	1336	1336	$ -	$ 128,291	$ 3,271,418	$ 3,399,709
2	2673	2673	$ -	$ 128,291	$ 3,271,418	$ 3,399,709
3	4009	4009	$ -	$ 128,291	$ 3,271,418	$ 3,399,709
4	5345	5345	$ -	$ 128,291	$ 3,271,418	$ 3,399,709
5	6682	6682	$ 4,800,000	$ 128,291	$ 3,271,418	$ 8,199,709
6	8018	8018	$ -	$ 128,291	$ 3,271,418	$ 3,399,709
34	45436	45436	$ -	$ 128,291	$ 3,271,418	$ 3,399,709
35	46773	46773	$ -	$ 128,291	$ 3,271,418	$ 3,399,709
36	48109	48109	$ 4,800,000	$ 128,291	$ 3,271,418	$ 8,199,709
37	49445	49445	$ -	$ 128,291	$ 3,271,418	$ 3,399,709

Once the costs per year of operation are computed, the total C-17 engine O&S cost for a given fleet alternative by calendar year can be computed by appropriate combination of the yearly costs. An example of how this is performed is given in Table 129. For this example, Lot 1 of 10 active aircraft begins operation in 2004, and Lot 2 of 10 active aircraft begins operation in 2005.

Table 129. Example Fleet C-17 Engine O&S Cost Estimate by Calendar Year

Year	Lot 1 O&S Cost By Year	Lot 2 O&S Cost By Year	Total O&S Cost by Year
2004	$ 33,997,091	$ -	$ 33,997,091
2005	$ 33,997,091	$ 33,997,091	$ 67,994,182
2006	$ 33,997,091	$ 33,997,091	$ 67,994,182
2007	$ 33,997,091	$ 33,997,091	$ 67,994,182
2008	$ 81,997,091	$ 33,997,091	$ 115,994,182
2009	$ 33,997,091	$ 81,997,091	$ 115,994,182
2037	$ 33,997,091	$ 33,997,091	$ 67,994,182
2038	$ 33,997,091	$ 33,997,091	$ 67,994,182
2039	$ 81,997,091	$ 33,997,091	$ 115,994,182
2040	$ 33,997,091	$ 81,997,091	$ 115,994,182

To estimate the total C-17 engine O&S costs for each fleet alternative, we require the number and type of each C-17 that will be added to the alternative fleets in each calendar year. Table 130 lists this data for each alternative that we analyze.

Table 130. Number/Type of C-17s Added by Calendar Year for Fleet Alternatives

	Number/Type of Aircraft (A-active/training, R-guard/reserve)									
Year Entering	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Alternative										
2 & 4	11R	2A/7R								
3 & 5	11R	15R	15R	4A/1R						
7	3A/8R	15A	15A	5A						
8	2A/9R	15A	15A	15A	15A	4A				
9	2A/9R	15A	15A	15A	15A	15A	15R	15R	15R	1A

Using the data we computed the estimates for the total C-17 engine O&S costs for each of these alternatives. The resulting cost estimates are given in Table 131.

Table 131. C-17 Engine O&S Cost Estimates by Calendar Year for Fleet Alternatives

Year	Alternatives 2 & 4	3 & 5	7	8	9
2004	$ -	$ -	$ -	$ -	$ -
2005	$ 18	$ 18	$ 23	$ 21	$ 21
2006	$ 36	$ 42	$ 74	$ 72	$ 72
2007	$ 36	$ 66	$ 125	$ 123	$ 123
2008	$ 36	$ 80	$ 142	$ 174	$ 174
2009	$ 36	$ 80	$ 157	$ 235	$ 235
2010	$ 46	$ 80	$ 214	$ 311	$ 348
2011	$ 36	$ 80	$ 214	$ 311	$ 373
2012	$ 36	$ 99	$ 166	$ 311	$ 397
2013	$ 36	$ 80	$ 157	$ 321	$ 431
2014	$ 98	$ 133	$ 253	$ 373	$ 540
2015	$ 70	$ 152	$ 214	$ 311	$ 425
2016	$ 36	$ 171	$ 181	$ 321	$ 434
2017	$ 46	$ 80	$ 214	$ 383	$ 497
2018	$ 36	$ 80	$ 214	$ 330	$ 502
2019	$ 36	$ 99	$ 166	$ 311	$ 425
2020	$ 36	$ 80	$ 157	$ 321	$ 506
2021	$ 46	$ 80	$ 214	$ 330	$ 569
2022	$ 89	$ 133	$ 253	$ 354	$ 545
2023	$ 70	$ 171	$ 166	$ 311	$ 425
2024	$ 36	$ 152	$ 157	$ 321	$ 434
2025	$ 46	$ 80	$ 214	$ 330	$ 502
2026	$ 36	$ 80	$ 214	$ 311	$ 425
2027	$ 36	$ 99	$ 166	$ 311	$ 425
2028	$ 36	$ 80	$ 157	$ 321	$ 506
2029	$ 46	$ 80	$ 214	$ 330	$ 574
2030	$ 89	$ 133	$ 253	$ 354	$ 540
2031	$ 70	$ 171	$ 181	$ 321	$ 434
2032	$ 46	$ 152	$ 214	$ 383	$ 497
2033	$ 36	$ 80	$ 214	$ 330	$ 502
2034	$ 36	$ 99	$ 166	$ 311	$ 425
2035	$ 36	$ 80	$ 157	$ 321	$ 434
2036	$ 46	$ 80	$ 214	$ 330	$ 569
2037	$ 36	$ 80	$ 214	$ 311	$ 502
2038	$ 89	$ 152	$ 205	$ 354	$ 540
2039	$ 70	$ 152	$ 157	$ 321	$ 434
2040	$ 46	$ 152	$ 214	$ 330	$ 502

b. Other CORE Elements

This Other CORE Elements segment of the C-17A O&S cost estimate addresses the cost elements presented in Table 132. In this table the cost elements are identified and comments pertinent to the cost element and/or associated estimate are provided. In addition to contractor logistics support, detailed estimates were developed for maintenance staffing, aircraft depot maintenance, modification kit procurement/ installation, and software maintenance.

Table 132. O&S Cost Elements Addressed as CORE Elements

Cost Element	Comments
Unit Mission Personnel	
Aircrew	Used crew ratios directed by HQ/AMC
Maintenance	Estimated current staffing based on information from AFI 65-503, HQ/AMC and ANG
Other Mission	Used AFI 65-503 staffing data to estimate
Aircraft Depot Maintenance • Excludes propulsion system	Estimated based scaling C-5 experience for PDM costs
Modification Kit Procurement/Installation	Used CORE model algorithm and adjusted costs higher to sustain objective MCR
• Contractor Logistics Support	Based on Boeing Proposal for Flexible Sustainment using FY 2005 as baseline
Indirect Support	
Personnel Support	Used CORE model algorithms to estimate
Installation Support	Used CORE model algorithms to estimate

The methods and sources of data used to estimate these costs and the cost estimates derived using these methods are reviewed below.

c. C-17 Unit Mission Personnel Costs

Active Unit Staffing. This segment addresses the active unit staffing estimates used in the O&S costs estimates for the various configurations of the C-17. In developing the estimate, we used the following staffing information from AFI 65-503 for a typical Active C-17 squadron with 18 PAA. In Table 133 we present the active aircrew staffing requirements provided by HQ/AMC, which were used without change in our study for all configurations of aircraft.

Table 133. C-17 Active Staffing Requirements for a Typical Active 18 PAA Wing

Program Factors	Number of Personnel Needed
PAA	18
Crew Ratio	3
FH/PAA/Yr	1470
Pilots/Crew	2
Non-Pilot Officer/Crew	0
Enlisted/Crew	1.5
II Manpower Factors	
PPE Officers	122
PPE Enlisted	558
PPE Civilian	76
BOS Officers	0
BOS Enlisted	30
BOS Civilians	10
RPM Officers	0
RPM Enlisted	4
RPM Civilians	5
MED Officers	2
MED Enlisted	7
MED Civilians	2
Unit Staff Officers	4
Unit Staff Enlisted	0
Unit Staff Civilians	6
Security Officers	0
Security Enlisted	22
Other Staff Officers	0
Other Staff Enlisted	0
Other Staff Civilians	0

In Table 134 we portray the current maintenance staffing for a C-17 active squadron as reported in AFI 65-503.

Table 134. C-17 Maintenance Staffing Requirements for a Typical Active 18 PAA Squadron

Staff Category	Number of Maintenance Personnel
Officers	10
Enlisted	477
Civilians	48
Total	534

C-17 Reserve Associate Unit Staffing. This segment addresses the Reserve Associate unit staffing estimates used in the O&S costs estimates for the two configurations of C-17: current and extended range. We used the current staffing information available in AFI 65-503 as the basis for our estimates. We present in Table 135 the total C-17 PPE staffing requirements for a Reserve Associate aircrew and maintenance staffing requirements. The AFI 65-503 aircrew staffing was used without change in our study for both configurations of aircraft. The maintenance staffing was adjusted to reflect the slight increase in manpower necessary for the extended range version of the aircraft.

Table 135. Air Force Reserve Associate Staffing Including Specific Staffing Adjustments Implemented in O&S Estimate

Program Factors	Number of Personnel Needed
PAA	54
Crew Ratio	3
FH/PAA/YR	0
Pilots/Crew	2
Non-Pilot Off/Crew	0
Enl/Crew	1.5

C-17 Air National Guard Unit Staffing. In developing the estimate for C-17 ANG staffing, we used the current staffing information provided by the National Guard Bureau and coordinated with ANG/XPP for our estimates. We present in Table 136 the total PPE staffing requirements for an ANG squadron of eight C-17 aircraft. This aircrew staffing was used without change in our study for all configurations of aircraft. The maintenance staffing was adjusted to reflect a slight increase in spaces per aircraft for the extended range aircraft configuration.

Table 136. C-17 Aircraft Air National Guard Unit Staffing Implemented in O&S Estimate

Factors	Number of Personnel Needed
PAA	8
Crew Ratio	5
FH/PAA/YR	
Crew	
Pilots	2
Total Pilots	80
Enlisted	1.5
Total Enlisted	60

Table 137 portrays for the weapon system staffing requirements for the current C-17 configuration. The maintenance staffing requirements would increase by 4 spaces per aircraft for the extended range version of the aircraft.

Table 137. Weapon System Staffing Requirements

Weapon System Total	Aircrew officer	Aircrew enlisted	Unit Staff + Security	Maintenance	Total
PPE Civilian Technicians		15	13	184	212
AG Officers	12			8	20
AG Enlisted		12	6	39	57
PPE Drill Officers	68		13	41	122
PPE Drill Enlisted		33	48	447	528
Total	80	60	80	719	939
Maintenance Spaces Per Aircraft				89.875	

C-17 Air Force Reserve Unit Staffing. This segment addresses the Reserve unit staffing estimates used in the O&S costs estimates for the two configurations of C-17 aircraft. Since we did not have a estimate from the AFR on the staffing for an Air Force Reserve C-17 Squadron, we used the current staffing information available for an ANG

C-17 squadron adjusted by the differences in types of positions as the basis for our estimates. We present in Table 138 the total PPE staffing requirements for AFR Squadron. This aircrew staffing was used without change in our study for all configurations of aircraft. The maintenance staffing was adjusted to reflect a slight increase in spaces per aircraft for the extended range aircraft configuration. Table 138 summarizes the weapon system staffing requirements for the current C-17 configuration. The maintenance staffing requirements would increase by four spaces per aircraft for the extended range version of the aircraft.

Table 138. C-17 Air Force Reserve Unit Staffing Implemented in O&S Estimate

Program Factors	Number of Personnel Needed
PAA	8
Crew Ratio	5
FH/PAA/YR	700
Pilots/Crew	2
Non-Pilot Officers/Crew	0
Enlisted/Crew	1.5
II Manpower Factors (Staffing Positions)	
PPE Total	939
PPE Drill Officers	47
PPE Drill Enlisted	531
PPE Civilian Technicians	260
PPE Civilians	17
BOS Drill Officers	11
BOS Drill Enlisted	21
BOS Civilian Technicians	10
BOS Civilians	11
RPM Drill Enlisted	5
RPM Civilian Technicians	2
RPM Civilians	6
Unit Staff Drill Officers	13
Unit Staff Drill Enlisted	48
Unit Staff Civilian Technicians	13
Unit Staff Civilians	4
PPE Active officers	48
PPE Active enlisted	36

d. Aircraft Depot Maintenance

This segment provides our estimates for aircraft depot maintenance costs for the C-17A aircraft reflecting a change in maintenance concept that expands the scope of an aircraft depot maintenance program beyond the currently planned Analytical Condition Inspection Program. This more-comprehensive aircraft depot maintenance program includes expanded inspections as aircraft ages, work to perform structural repairs that address corrosion and unpredictable fatigue problems, and a retrofit program to fix specific structural problems that can be predicted from current C-17 structural test and aircraft use information. Our approach to estimating the aircraft depot maintenance O&S costs is to derive a steady state estimate that takes into account the potential for cost growth as the C-17 fleet ages. In the structure O&S cost segment that follows, we estimate specific aircraft retrofit actions that will have to be accomplished to keep the structural integrity of the C-17 fleet healthy through 2040. Although a significant amount of the projected retrofit costs would be incurred in aircraft depot maintenance activities, those are over and above the costs projected in this segment. Also, the retrofit costs do not include the repair work needed to expand the structural inspections needed as the aircraft ages and to address corrosion problems. The corrosion problems, which cannot be easily predicted as the fleet ages, and other unpredictable structural repair actions, will be needed to keep the fleet healthy. All of the latter costs are addressed in this estimate of aircraft depot maintenance costs.

Currently the C-17 aircraft depot maintenance is based on an ACI program where a C-17A aircraft is inducted every 10 years. The typical types of work performed during ACI include ACI annual tasks (ACI annual fix hours, ACI phased tasks, ACI phased fix hours, incoming processing, aircraft painting, flight prep tasks, and delivery tasks.)

The ACI program for the C-17 is now being conducted by the Boeing Company under the Flexible Sustainment Contract. Our estimate is based on the assumption that C-17A will require an expanded level of depot maintenance work with aircraft induction every 10 years. Our estimate was derived by scaling the C-17 recurring flyaway costs and aircraft empty weight to the C-5 recurring flyaway cost and aircraft empty weight, and adjusting the estimate to account for the improved material content in the C-17 versus the C-5A/B. This results in an estimate of an average depot maintenance cost of $2.23 million per aircraft, which occurs every 10 years.

e. Modification Kit Procurement and Installation

The modification and kit procurement and installation O&S costs address the reliability, maintainability, and safety modifications needed to allow a weapon system to perform its original mission over its operating life. Using the same approach we used for the C-5, we arrived at the following sustaining engineering costs per year for the current configuration of $98,686, baseline configuration of $100,805, partial upgrade of $128,412, and full upgrade of $153,470. This provided an increase of greater than 50 percent in sustaining engineering funds when comparing the full upgrade configuration to the experience with current configuration.

Our estimate of the O&S cost for the sustaining engineering provides engineering support that is not covered under the contractor logistics contract but is necessary to ensure a weapon system operates safely and effectively throughout its operating life. The tasks include problem definition for both hardware and software elements of the aircraft and for hardware problem resolution through studies, initial designs, breadboard prototypes, and/or engineering change proposals. In the O&S cost estimate for the C-17, there are two activities that cover sustaining engineering functions: the Contractor Logistics Support and the resources that cover the integration and work on the common items used on the aircraft. The cost for the common sustaining engineering effort is $10,470 per PAA and was derived from the Air Force Total Ownership Cost data base for FY 1998 as a basis to estimate these costs.

f. Post-Deployment Software Support

We have reviewed the information provided by the C-17 System Program Office that defines the size and complexity of the software that the Air Force and Boeing plans for the baseline configuration of the C-17A aircraft. Using this information, we estimated the C-17 post deployment software support costs to be $22.8 million per year, which translates into a cost per PAA for cases where no additional C-17s are procured at approximately $218,000.

g. Contractor Logistics Support

Our estimate for CLS is based on the Flexible Sustainment program currently providing logistics support to the C-17 program. For our estimate, the costs for a selected subset of tasks now covered by Flexible Sustainment have been developed. The estimate for CLS includes the following types of tasks now supported through Boeing's Flexible Sustainment Contract:

- Peculiar C-17 consumables
- Peculiar C-17 reparables
- Includes both repair and condemnation replacement
- Peculiar Sustaining Engineering
- Technical Field Support
- Material Management—configuration management, requirements determination
- Base-level engine test cell support.

Boeing provided us with a copy of their Flexible Sustainment Proposal, which covers periods through FY 2007. We used the proposal and compared the proposal with the C-17 System Program Office provided Flexible Sustainment Cost Status Report (CSR.) The cost per flying hour to provide the work defined as contractor logistics support is $1,922 per flying hour.

B. RESIDUAL VALUE AND DISPOSAL COSTS

The residual value and disposal costs were included to properly account for any residual life that could exist at the end of FY 2040 for the C-17 and the disposal costs of deactivating a C-5 and removing it from inventory in those options that substitute C-17s for C-5s.

1. Residual Value

The C-5 was assumed to have no residual value in FY 2040, but the residual value for the C-17 would be based on the remaining life in FY 2040 for each aircraft as measured by flying hours.

A fleet of newer aircraft clearly has greater value than a fleet of older aircraft, and this can be an important difference among alternatives. Our study recognized the need to account for these differences in fleet value at the end of the study period, so that an alternative that would produce a fleet with significant remaining life would be appropriately credited in the analysis. For the C-5s, we assumed that the residual value would always be the scrap value. Even for those several alternatives where C-5s are retired early, we assumed that there would not likely be a market for selling them except for parts and scrap value. Therefore, the discussion of residual value pertains to the C-17 aircraft only.

We chose remaining fatigue life as a measure of the C-17's residual value at the end of the study period. We recognize that many factors determine an aircraft's value, including suitability for the contemporary military environment, the condition of subsystems, corrosion, the maintainability of the aircraft as parts become difficult to obtain, compliance with regulations such as noise requirements, and even the market for used aircraft. We chose remaining airframe fatigue life as our metric because renewal of large fatigued structure can be a significant investment that would contribute to a retirement decision, and because fatigue life lends itself to meaningful projections. Projections of most other factors would be almost entirely speculative.

The remaining life of each aircraft in the C-17 fleet was calculated, using the study's flight hour rate assumptions and recent flying severity. We examined both the wing and fuselage to determine the end of each aircraft's fatigue life. Wing life is driven largely by the number of flight hours flown, while fuselage life is driven by the number of pressure cycles applied. Both areas were projected independently. An aircraft's remaining life was the minimum of the fuselage remaining life and the wing remaining life. Residual value was then calculated by multiplying the percentage remaining life multiplied by the acquisition cost. This latter calculation was done only if the aircraft had at least 5 percent of its total lifetime remaining. Otherwise, it was scrapped.

2. Disposal Costs

For C-5 disposal costs, we received estimates from Aerospace Maintenance and Repair Center (AMARC) indicating the expected costs and value of sales from the bulk materials and spare parts. The available information from AMRC indicates that the funds received by the Government from sale of bulk materials and the return of selected spare parts would significantly exceed the costs of disposing of the aircraft.

For all the C-5 fleet and those C-17 aircraft that had less than 5 percent of its lifetime remaining, we calculated the value of scrapping—money received for the scrap material less disposal costs. We consulted with the Air Force to obtain estimates of the scrap value of each aircraft. The data provided to us showed that they received a return on cost of 15 to 1 for processing aircraft and selling the scrap material. We estimated total cost for the C-5 for transporting, demilitarizing, and removing parts to be $75,000. Thus, for the C-5, we estimated a net scrap value after processing of $1.05 million. For the C-17, the net scrap value was $1.0 million. The major reason for the slight difference was the aircraft size difference.

3. Summary Results

Table 139 presents the results of the residual plus disposal value for each of the alternatives. It should be recognized that many of the costs represented by these values are realized at the end of 2040, at which time the discount factor is 0.314. Therefore, a present value analysis will give much lower weight to this cost metric because of the very high discount factor. The table shows the combined residual plus disposal value in both constant year and discounted millions of FY 2000 dollars. Note that these are negative costs, i.e., they subtract from the total life cycle costs of the alternatives. It is seen that the alternatives that have large C-17 buys have the greater residual values since the C-17 will have some useful life at the end of the analysis. This is particularly true for Alternative 8, with a 75 aircraft buy, and Alternative 9 with a 132 aircraft buy. The former has a constant year residual value of $960 million, which reduces to about $415 million after discounting. For Alternative 9, the comparable values are $2.4 billion and $0.9 billion, for the constant year and discounted values, respectively.

Table 139. Residual and Disposal Value for Each Alternative at FY 2040

Alternative	Residual and Disposal Value ($M FY00)	
	Constant Year Dollars	Discounted Dollars
1	132.30	41.57
2	152.30	47.85
3	340.43	106.96
4	152.30	47.85
5	340.43	106.96
6	132.30	41.57
7	340.43	106.96
8	957.04	413.98
9	2,380.07	881.84

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GLOSSARY

GLOSSARY

ACI	Analytical Condition Inspection
AFCAA	Air Force Cost Analyses Agency
AFCEAA	U.S. Air Force Cost and Economic Analysis Agency
AFI	Air Force Instruction
AFOTEC	Air Force Operational Test & Evaluation Center
AFR	Air Force Reserve
AFTOC	Air Force Total Ownership Cost
ALC	Air Logistics Center
AMARC	Aerospace Maintenance and Repair Center
AMC	Air Mobility Command
AMLG	aft main landing gear
AMP	Avionics Modernization Program
ANG	Air National Guard
AoA	Analysis of Alternatives
ARC	Air Reserve Component
BAI	Backup Aircraft Inventory
BES	Budget Estimate Submission
BURU	Bottom-Up Review Update
CAIG	Cost Analysis and Improvement Group (OSD)
CCDR	Contractor Cost Data Report
CDF	cumulative distribution function
CER	cost estimating relationship
CFD	computational fluid dynamics
CFE	contractor-furnished equipment
CLS	contractor logistics support
CPA	cost per aircraft
CPH	cost per flying hour

CRI	Cost Reduction Initiative
CSR	Cost Status Report
DLR	depot level reparable
DMIL	demilitarizing
DR	departure reliability
EFH	engine flying hour
EGT	exhaust gas temperature
EMD	engineering and manufacturing development
FAA	Federal Aviation Administration
FADEC	full authority digital electronic controller
FH	flying hour
FMC	full mission capable
FMLG	forward landing gear
FOD	foreign object damage
FSL	Full System List
FY	fiscal year
GATM	Global Air Traffic Management
GE	General Electric
GFE	Government-furnished equipment
GSD	bulk supply
GSD	General Support Division
HNS	host nation support
HS	Home Station
IAT	Individual Aircraft Tracking
ICAO	International Civil Aviation Organization
IME	inherent maintenance events

LCC	life-cycle costs
LCF	low cycle fatigue
LLP	life-limited part
MADARS	Malfunction Detection, Analysis and Recording Susbystem
MAJCOM	Major Command
MCR	Mission Capable Rate
MESL	Minimum Essential Subsystems List
MILCON	military construction
MLG	main landing gear
MDS	aircraft type
MMH	maintenance man hours
MRS	Mobility Requirements Study
MSD	consumable parts and depot-level reparables
MSD	Material Support Division
MTBF	mean time between failures
MTM/D	million ton miles per day
MTW	Major Theater War
MYP	Multiyear Proposal
NLG	nose landing gear
NMC	not mission capable
NMCR	not mission capable rate
NMCS	Not Mission Capable Supply
NTF	no trouble found
O&O	oversize and outsize
O&S	operations and support
OMB	Office of Management and Budget
ORD	Operational Requirements and Document
OSD	Office of the Secretary of Defense
PAA	Primary Authorized Aircraft
PAI	Primary Aircraft Inventory
PDM	Programmed Depot Maintenance

PMC	partially mission capable
POE	posture of engagement
POM	Program Objective Memorandum
PPE	Primary Program Element
PV	present value
PW	Pratt and Whitney
QEC	quick engine change
R&M	reliability and maintainability
RDT&E	research, development, test, and evaluation
RERP	Reliability Enhancement and Re-engining Program
ROM	rough order of magnitude
RR	Rolls Royce
SA-ALC	San Antonio Air Logistics Center
SAF/AQ	Assistant Secretary of the Air Force for Acquisition
SCC	stress corrosion cracking
SE	support equipment replacement
SFC	specific fuel consumption
SOF	Special Operations Forces
SPO	System Program Office
TAI	Total Authorized Inventory
TR	thrust reverser
USAF	United States Air Force
V&V	verification and validation
WMD	weapons of mass destruction
WR-ALC	Warner Robins Air Logistics Center
WUC	work unit code

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13. ABSTRACT *(Maximum 200 words)*

This two-volume report provides cost and reliability analyses to support a DoD Analysis of Alternatives (AoA) to determine the most cost-effective means for meeting future strategic airlift needs. Volume I contains the main report at the unclassified level. Volume II summarizes the company-sensitive and proprietary information used to conduct the analyses and is not available for general distribution. In the report, both modernized re-engined C-5s and additional C-17s are AoA candidates. Some of the alternative airlift fleets considered contain modernized C-5s, others retire the C-5s and replace them with new C-17s, and others include a mixture of C-5s and new C-17s. This report determines the mission capable rates of all candidate strategic airlifters within these fleets and estimates life cycle costs for all alternative fleets. It also includes modernization excursions, sensitivity analyses, and cost risk analyses.

14. SUBJECT TERMS

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